GEOLOGY OF THE MUTTON BAY INTRUSION AND SURROUNDING AREA
NORTH SHORE, GULF OF ST. LAWRENCE, QUEBEC

by

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GEOLOGY OF THE MUTTON BAY INTRUSION AND SURROUNDING ROCKS

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Abstract

Geology and structure of 1,000 square miles of granulite-upper amphibolite facies gneisses cut by syn- and late-kinematic intrusions are described.

The circular post-kinematic Mutton Bay alkaline syenite (631 m.y.) is divided into three main intrusive groups on the basis of chemistry, mineralogy, and field relations. Differentiation includes gravity settling and flow differentiation, while intrusion involved early stoping and assimilation with late faulting. Depth of the present level below the roof of the intrusion is estimated at 6-8 miles and temperature of crystallization of felspars in the early magmas at greater than 1015°C at less than 500 bars water pressure. Orthoclase inverted to microcline in foliated rocks that intruded as crystal mushes.

A giant gabbro dyke with syenite differentiate (470 m.y.) is intruded by diabase and trachyte dykes. Carbonate enrichment in the trachytes is accompanied by high potash felspar content. Sandstone dykes are the only Paleozoic sediments.

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INTRODUCTION

General Statement

The geology of the eastern part of the Grenville Province is poorly known even though it is accessible. This is probably due to the lack of important mineral discoveries, its distance from the industrial centres, and the little interest generally shown by mining companies for areas of high grade metamorphic rocks.

In 1962 the writer initiated a program of geological mapping in the area between St.Augustin and Tête-à-la-Baleine on the North Shore of the Gulf of St.Lawrence, on behalf of the Geological Survey Branch of the Quebec Department of Natural Resources, at a scale of 1 inch = 1 mile. This thesis represents the results of the work carried out during the summers of 1962 to 1965 in an area covering approximately 1,000 square miles.

Location

The area is part of the southeastern plateau belt of Labrador-Ungava. It lies on the North Shore of the Gulf of St.Lawrence about 350 miles east of Sept-Iles and 700 miles east of Quebec City (fig.1). The area is composed of three map sheets (back pocket) : the St. Augustin area sheet bounded by longitudes 58°30' and 58°45' and latitudes 51°09' and 51°27' ; the Cook-d'Audhebourg area sheet bounded by longitudes 58°30' and 59°00' and latitudes 51°00' and 51°10' ; and the Baie des Moutons area sheet bounded by longitudes 58°45' and 59°15' and latitudes 50°35' and 51°00'. Included in the area are Boishébert and parts of Montesson, Céry, d'Audhebourg, Cook, and Bougainville townships in Duplessis County, and, from west to east along the coast, the villages of Tête-à-la-Baleine (summer village), Baie-des-Moutons (Mutton Bay), Tabatière, Lac Salé, Baie-de-la-Terre (abandoned in 1966), and St.Augustin.

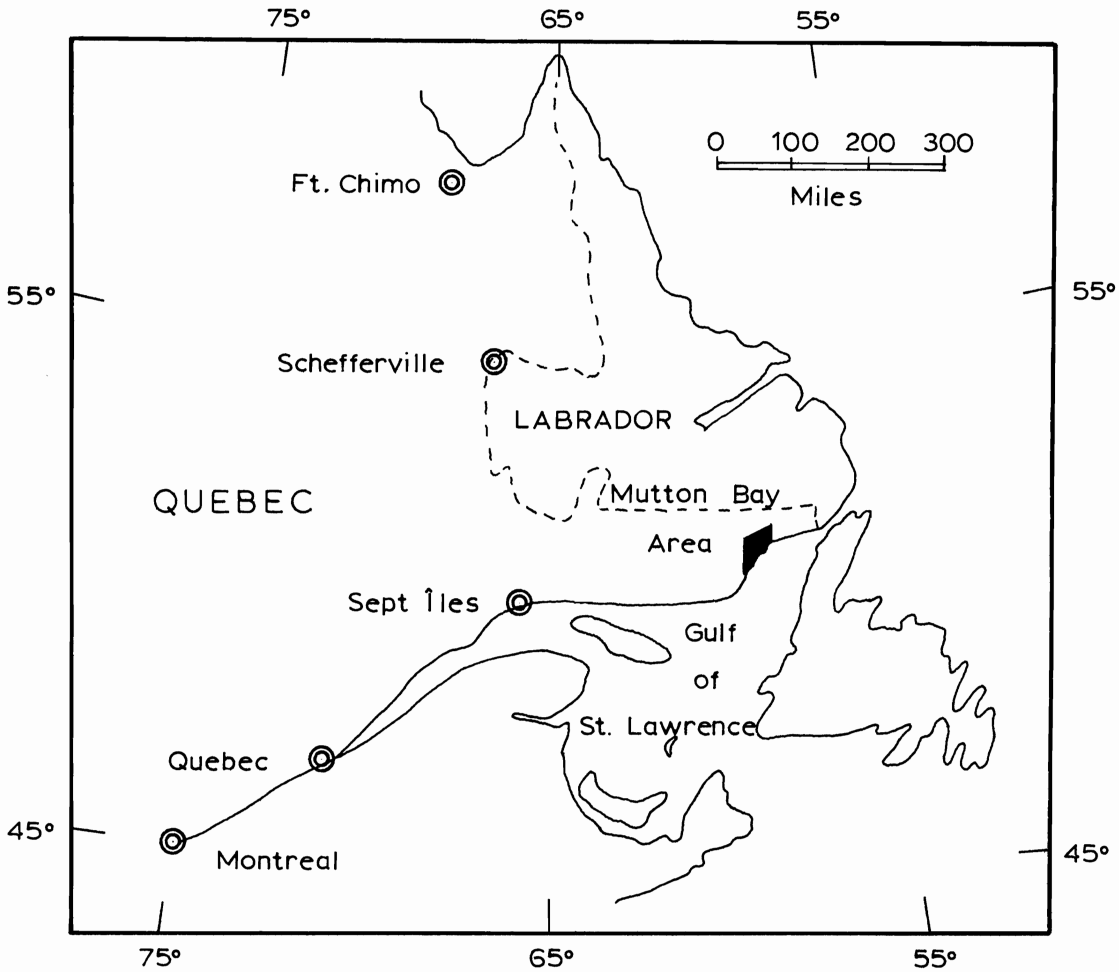

Fig. 1 - Index Map

Access

Tête-à-la-Baleine, Baie-des-Moutons, Tabatière, and St.Augustin may be reached by ship (Clarke Steamship Co. Ltd.) leaving either from Quebec fortnightly or from Rimouski via Sept-Iles weekly. Planes

(Northern Wings Ltd.) run at least tri-weekly from Havre-St-Pierre or Sept-Iles, weather permitting. No villages east of Havre-St-Pierre have hotels and one must seek accommodation with private families. Most of the area is coastal and readily accessible by boat. Numerous lakes and rivers with well-cut portages provide access to the interior.

Field Work

Base maps were compiled by Aéro Photo Inc. Quebec at a scale of 2 inches = 1 mile from aerial photographs obtained from the R.C.A.F. and controlled by triangulation. Nautical charts, at a scale 1 : 36501 and published by the Department of Mines and Natural Resources, Ottawa, were of considerable value in mapping the coastal section.

Mapping was carried out at a scale of 1 inch = 1 mile. Coastal shorelines, and those of larger lakes and streams, were examined in some detail. Intervening ground was covered by traverses spaced at approximately 1/2 mile intervals. Traverses were run from point to point, and positions of points of interest marked on an acetate overlay on an airphoto. Normal pace and compass traverses were impractical due to the ruggedness of the terrain and the difficulty of keeping to a straight line.

Forested areas are sparse and are confined to river valleys and a few sheltered slopes. Tops of hills and coastal islands have only a thin covering of moss and there are numerous exposures of bare rock. Because of the abundant exposure, only those outcrops at which geological information was recorded are marked on the maps. It should be pointed out that coastal shorelines consist of almost continuous outcrop.

The writer was ably assisted in the field during the summers 1962-1965 by senior assistants B.Warren, F.Fenzel, and R.Larocque ; junior assistants P.Villard, P.Lavoie, G.Simard, and F.Gilbert ; canoemen T.Maurice, G.Lavallee, C.Kennedy, and cook J.Belvin.

Laboratory Work

A total of 300 thin sections were studied. Plagioclase compositions were determined with the universal stage by measuring extinction on grains perpendicular to 001 and 010 and using the curve given by Winchell and Winchell (1959, p.283) after Duparc and Reinhard (1924) which makes no allowance for high or low temperature forms. $2V_x$ was measured on potash felspar in the syenitic rocks. 2V and extinction angles were determined on amphiboles and pyroxenes and referred to curves of Tröger (1959). $2V_x$, referred to the curve of Deer, Howie, and Zussman (1962, vol.1, p.22), was used to determine the composition of olivines. Index of refraction, Ny, was used to study the variation in the biotite composition of the syenitic rocks. 8 biotites from rocks of the Mutton Bay intrusion were analysed by J.Stevenson and J.Volrath of the McGill Geochemical Laboratory and were used to establish the element substitutions that cause the index variation. Several biotite crystals were scanned with the electron probe by W.MacLean to check the possibility of zoning. Indices of refraction, with reference to Winchell and Winchell (1959, p.353), were used to determine the composition of the scapolite. 12 polished sections were made for identification of the opaque minerals. A number of syenitic rocks were stained as a check for the possible presence of felspathoids, using the method described by Shand (1939).

A number of minerals were identified, or their identification confirmed, using an x-ray diffractometer. X-ray diffraction was also used to determine obliquity and type of potash felspar, and structural type of plagioclase in microperthites of the syenites.

Complete chemical analyses of 9 rocks of the syenite suite were provided by the Department of Natural Resources, Quebec. 17 partial analyses of microperthites, 11 of trachyte dykes, and 1 of a carbonate dyke were performed by the writer, using chemical methods for Ca and CO_2 and flame photometry for Na and K. Microperthite concentrates were obtained using heavy liquids and the Franz isodynamic separator.

2 Rb/Sr and 2K/Ar age determinations were made by Dr.R.Doig of the McGill Isotope Laboratory on biotites that were separated using a water flotation process devised by the author (Davies, 1966).

Modal analyses were made on 27 syenite specimens. Each analysis was made on an unstained slab with an area 100 times the maximum grain size using the method of Jackson and Ross (1956), and was combined with an analysis on one or two thin sections as suggested by Nesbitt (1964). A minimum of 1000 points was counted in each case. Felspar, quartz, olivine + pyroxene, biotite + amphibole, iron oxides, and sulphides were readily determined on the slab. Accessory and alteration minerals and the ratio of olivine to pyroxene and biotite to amphibole were determined in the thin sections. Modal analyses of other rocks were on single thin sections, counting 500-2000 points.

A total of about 1200 lineations, 1250 foliations, and 1725 joints in the gneisses, 1100 joints and 63 lineations in the syenite, and the orientation of 1100 dykes were analysed using equal area stereographic projections. In addition the widths of the dykes, and orientation, size, and number of phenocrysts within a number of dykes were analysed.

Specific colours mentioned throughout the thesis refer to the Rock-Color Chart distributed by the Geological Society of America. Shorter and more general colour terms are used in naming some rocks.

Acknowledgments

The writer is indebted to Rev. Father Paul Langlios O.M.I. at St.Augustin for valuable assistance given to the party throughout the summers ; also to the many people of St.Augustin and Tabatière whose help, co-operation, and advice are greatly appreciated.

The writer is especially grateful to Professor E.H.Kranck of McGill University who suggested the area as a thesis topic and directed the thesis, to Dr. M.Morin of the Quebec Department of Natural Resources for valuable discussion in the field, to Dr. R.Doig of McGill University for providing the age determinations, to J.Stevenson and J.Volrath of the McGill Geochemical Laboratory for eight biotite analyses, to H.Soutar for demonstrating the chemical methods used by the author, and to W.MacLean for scanning several biotite samples with the electron probe. Discussions with members of staff and graduate students at McGill University were of considerable help in the preparation of this thesis.

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Finally the author wishes to thank the Quebec Department of Natural Resources for making it possible to carry out the field work and for permission to use the data collected in this thesis.

Previous Work

De Puyjalon (1899) reported on the minerals of the North Shore including the Mutton Bay area. Longley (1944a, 1944b) described briefly the area between Aguanish and Lobster Bay and in more detail the Lobster Bay nickel prospect. Hale (1962) did a reconnaissance survey of an area covering 7,000 square miles including the Mutton Bay area, and describes very generally the economic and geological features of the district. Preliminary reports on the area have been published by the writer (1963, 1965a, 1965b), and Warren (1964), senior assistant in 1962, studied some intermediate intrusives immediately east of the area. An expedition in 1966 to the Mécatina Basin west of Mutton Bay, led by D.P.Gold, spent three weeks sampling and collecting structural data on the Mutton Bay pluton. A petrological study of the dykes is being made by J.Gerencher and some preliminary findings have been reported by Gold and Gerencher (1967).

DESCRIPTION OF THE AREA

Settlement and Resources

Most inhabitants are of European extraction and are predominantly French-speaking at Tête-à-la-Baleine and English-speaking in the other villages. A number of Indian families live at St.Augustin.

Fishing and hunting provide a living for most families. Small sawmills produce lumber for local needs and a number of men are occupied building houses and boats. A fish-processing plant, situated at Tabatière, provides work during the summer months. Many younger men seek work at Sept-Iles during the summer and the government winter works program is becoming more popular than the traditional hunting during the winter.

The greatest potential industry of the area is tourism. The area is scenically the most beautiful part of the coast. Its rugged countryside is unobscured by trees and there is an abundance of protected coastline. Wildlife abounds and fishing is excellent.

Land suitable for agriculture is found only in the valleys of Rivière St-Augustin and Rivière St-Augustin-Nord-Ouest. The whole area is classed as coastal tundra (Hare, 1959) and the few wooded areas are confined to valleys with the higher ground covered by moss, forest scrub and bare rock. Common trees are black and white spruce, balsam fir, white birch, and tamarack. Alders and willows dominate along the banks of streams. The largest trees in the area have an average diameter of 24 inches (2 feet above ground) but are not abundant.

Fish and Game

Large game seen by the party include caribou, black bear, and wolf. Beavers were plentiful and snowshoe hare and red squirrel common. Also seen were porcupine, muskrat, red fox, otter, ermine, and woodchuck. Mink, marten, lynx, and mole are reported by local trappers. Seals, porpoises, and whales are common along the coast. Bird life abounds and the area, which is the breeding ground of many species of waterfowl, has two bird sanctuaries.

Fishing is the major industry and Atlantic salmon, cod, trout, herring, mackerel, and capelin account for the major production. Quantities of lobster and scallops are also taken.

Weather

During the summer the prevailing winds are from the southwest, northeast, and west, and secondary winds are from the north, east, and south. Temperatures are cool during the same period and the Atlas of Canada (1957) gives the mean daily temperature during April as 25-30°F, July 55-60°F, and October 35-40°F. The mean number of frost-free days is 100-120 and the growing season 120-140 days. There is a mean precipitation of 8-10 inches during the period June-August, and over the summer an average of 10-20 days of fog. Due to precipitation, wind, and fog, 2-3 working days a week were lost by the party while mapping along the coast.

Physiography

Topography

The area is part of the southeastern plateau belt of Labrador-Ungava (Hare, 1959), which includes the country south of Lake Melville and the Lake Plateau, and east of Romaine river, excluding the Mealy Mountains. This physiographic division is for the most part a rough undulating plateau and the Mutton Bay area lies along the southern margin which is severely dissected. It is barren and for the most part consists of bare rock, swept clear of glacial drift during marine submergence.

Deep valleys and runs (submerged valleys) between islands form a well-defined pattern and were developed in pre-glacial times by subareal erosion of fracture zones. Between the major valleys differential weathering of gneisses has produced a homoclinal valley and ridge topography. The Mutton Bay intrusion forms a resistant mass rising 500-600 feet above the surrounding gneisses and is the highest part of the area (884 feet). Local relief in the gneisses is about 500-700 feet inland and decreases towards the coast.

Drainage

The only major rivers in the area are Rivière St-Augustin and Rivière St-Augustin-Nord-Ouest which flow in alluvium-filled valleys wide enough to allow meandering, and are generally independent of local structures. Most of the area is drained by systems of lakes and connecting streams strongly dependent on local structure, such as the Rivière du Gros-Mécatina, Lac Blais - Lac à Charles, Étang Belon, and Lac La Sarre systems. Larger streams and lakes follow fracture zones and smaller ones the foliation of the gneisses. The drainage pattern in the gneisses is rectangular, but a radial pattern is developed around the Mutton Bay intrusion.

Physiographic History of the Area

The Mutton Bay area lies on the southeastern boundary of the Canadian Shield and its physiographic history is clearly related to that of the shield as a whole.

The area was reduced to a peneplained surface by Cambrian time. Sandstone dykes in the area (probably Early Paleozoic) indicate very little erosion of the pre-Paleozoic land surface. At some time prior to the last glacial period the area stood at a higher level than today and allowed the development of a youthful drainage system with deep valleys.

Pleistocene glaciation modified the land surface, smoothing off the hills, gouging out depressions, and making valleys parallel to ice movement U-shaped. Transverse valleys developed cliffs on the north side and cirque-like hollows can be recognized on the Mutton Bay intrusive.

Retreat of the glaciers left the area covered by a thin veneer of till and erratic boulders. The area was submerged to about the present 410 foot contour level (Davies, in preparation) and clays were deposited in the deep submerged valleys.

Wave action during emergence washed the land surface below the level of maximum marine submergence free of glacial debris. The advancing mouth of St.Augustin river deposited sand and gravel over the clay. These sands and gravels are being eroded today and occur as terraces in St.Augustin valley and on islands around St.Augustin Bay.

GENERAL GEOLOGY

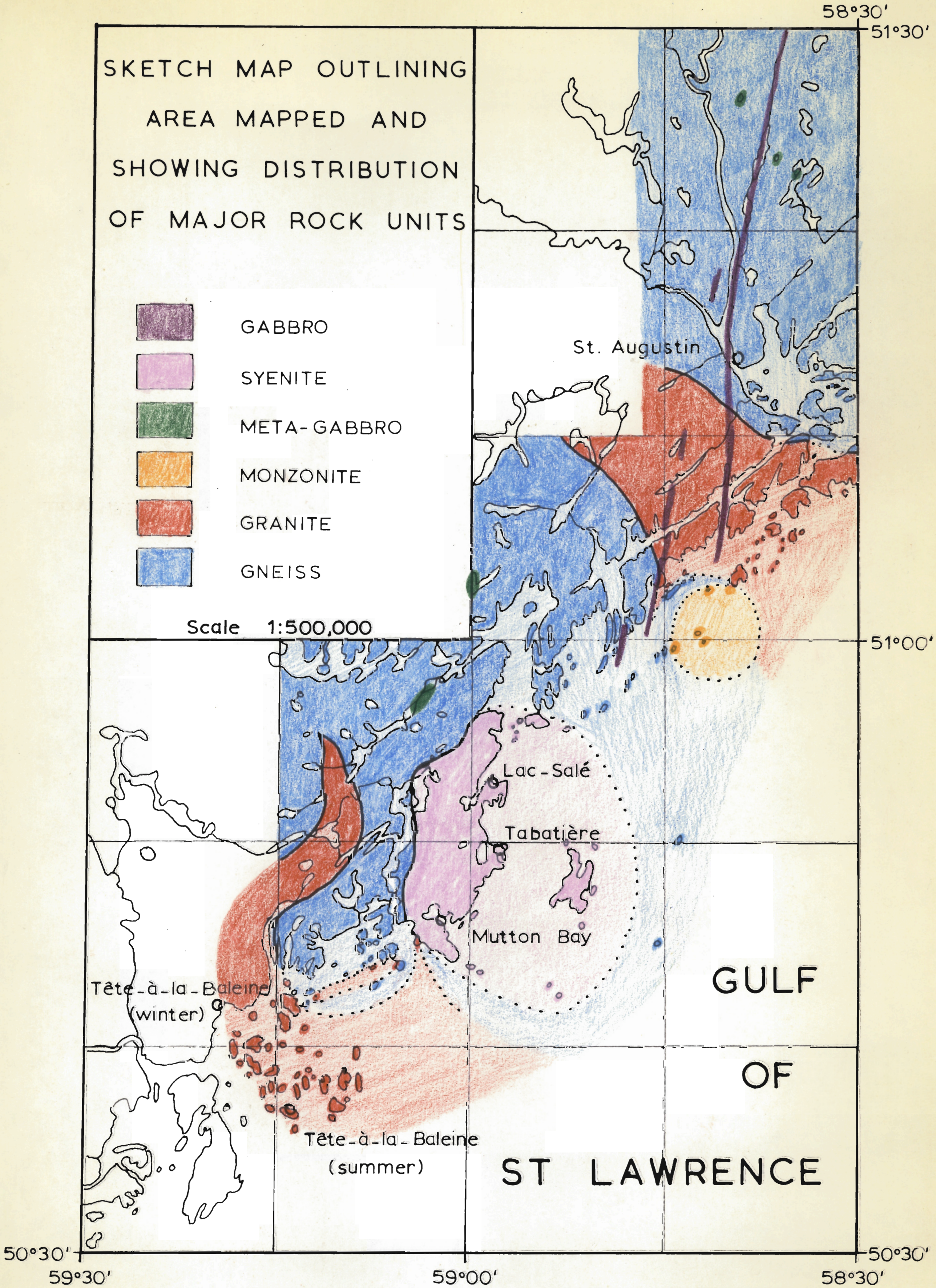
GENERAL STATEMENT

The Mutton Bay area lies in the eastern portion of the Grenville subprovince. Most of the consolidated rocks are Precambrian, the exceptions being the younger gabbroic and trachytic dykes and rare sandstone dykes which are believed to be Paleozoic. The distribution of the major rock types is shown in fig.2 and age relations are shown in Table I.

The oldest Precambrian rocks are gneisses belonging to the granulite and upper amphibolite metamorphic facies. The gneisses range in composition from granitic to quartz-dioritic and include accepted paragneisses which may carry sillimanite, garnet, and cordierite. Narrow quartzites and calc-silicate rocks are commonly interlayered. Amphibolites occur as both conformable layers and dykes. The above rocks are typical of the Grenville A subprovince of Osborne and Morin (1962).

Porphyritic granite and granodiorite occur as domes, conformable layers, and occasionally as discordant stocks, and were emplaced before or during folding. Small discordant stocks and dykes of granite to granodiorite-monzonite are post-folding but are still affected by thermal metamorphism. Intruded at about the same time were small discordant bodies of olivine gabbro.

The Mutton Bay alkali-syenite intrusion is a Late Precambrian circular body which transects the gneisses and is unaffected by regional metamorphism. The youngest intrusives are giant Ordovician gabbro dykes which are cut by small diabase and trachytic dykes.



SKETCH MAP OUTLINING AREA MAPPED AND SHOWING DISTRIBUTION OF MAJOR ROCK UNITS
GABBRO
SYENITE
META-GABBRO
MONZONITE
GRANITE
GNEISS
Scale 1:500,000
St. Augustin
Lac-Salé
Tabatière
Mutton Bay
Tête-à-la-Baleine (winter)
Tête-à-la-Baleine (summer)
GULF OF ST LAWRENCE
58°30'
51°30'
51°00'
50°30'
59°30'
59°00'

Fig. 2

Table I

Table of Formations

Pleistocene and Recent	Sand, silt, gravel, clays, peat
Unconformity	
Paleozoic	Diabase and related dykes, carbonate veins
	Intrusive Contact
	Giant gabbro dykes (470 m.y.)
	Intrusive Contact ?
	Sandstone dykes
Unconformity	
Late Precambrian	Satellitic dykes of the Mutton Bay syenite
	Intrusive Contact
	Mutton Bay syenite suite (631 m.y.)
Intrusive Contact	
Precambrian (Affected by Grenville Event)	Pegmatite and aplite Intermediate dykes and sills : granodiorite, quartz-monzonite, monzonite, orthoclase diorite
	Intrusive Contact
	Ile Lecouvre and related intrusives
	? ? ? ? ?
	Olivine gabbro
	Intrusive Contact
	Meta-gabbro (including amphibolite)
	Intrusive Contact
	Pegmatite Interlayered meta-gabbro (including amphibolites) Porphyritic granite and granodiorite
	Probable Intrusive Contact (or intrusive contact in part)
	Green pyroxene-plagioclase gneisses (+ cordierite and garnetiferous varieties) Fine- to medium-grained pink granitic gneiss Grey garnetiferous-biotite-plagioclase gneiss Light grey plagioclase gneiss Sillimanite-biotite-garnet gneiss Calc-silicate rocks Quartzite (+ sillimanite and garnetiferous varieties) Banded fine-grained pink and grey gneisses Dark grey biotite-hornblende gneiss

Narrow sandstone dykes are probably Cambrian or Ordovician and are the only consolidated sediments that are unmetamorphosed. Unconsolidated material of Pleistocene and Recent age is widespread but in minor quantities. Glacial material to an elevation of 410-420 feet has been reworked and concentrated in valleys and depressions.

RADIOMETRIC AGES OF ROCKS IN THE MUTTON BAY AREA

Five radiometric age determinations have been made on biotites from rocks in the area (Table II). A K/Ar age on a biotite from a biotite gneiss has been reported by Fortier and Lord (1961). Two K/Ar and two Rb/Sr ages, reported for the first time, are on biotites from igneous rocks collected by the author and kindly determined by Dr.R.Doig at the Isotope Geology Laboratory, McGill University.

Table II

Source	Method	Material	Age
Giant gabbro dykes	Rb/Sr	biotite	470×10^6 yrs $\pm$ 55×10^6 yrs
Mutton Bay intrusion (Early group)	Rb/Sr	biotite	631×10^6 yrs $\pm$ 40×10^6 yrs
Mutton Bay intrusion (Early group)	K/Ar	biotite	580×10^6 yrs $\pm$ 25×10^6 yrs
Mutton Bay intrusion (Late group)	K/Ar	biotite	592×10^6 yrs $\pm$ 20×10^6 yrs
Biotite gneiss	K/Ar	biotite	965×10^6 yrs $\pm$ 60×10^6 yrs at 1000×10^6 yrs

Biotite gneiss

The 965 m.y. age is that of the last metamorphism and corresponds to the Grenville 'event'.

Mutton Bay intrusion

The Late Precambrian age of the Mutton Bay syenite intrusion sets it apart from the syenites of the anorthosite suite of the Grenville province. It is a low level intrusion similar to a number of syenites in the Montreal area and, in particular, to the Chatham-Grenville syenite which has a similar K/Ar age of 640 m.y. (Philpotts and Miller, 1964) and a similar structural setting, lying on the break between the Paleozoics and the uplifted Shield.

A syenite on the Labrador coast may be of a similar age. Lamprophyre dykes described by Kranck (1953) which are possibly related to the syenite have been dated as 570 m.y. by the K/Ar method on biotite (King and Stockwell, 1963).

Giant gabbro dyke

The giant gabbro dyke is the only intrusive whose age relative to the Mutton Bay intrusion could not be determined in the field. The biotite in the gabbro is primary and the dyke shows no sign of metamorphism.

On the northern side of the Strait of Belle Isle, between Chateau Bay and Torrant Point, basalt layers with columnar jointing form the crests of shore cliffs and overlie sandstone (Kranck, 1939a and b ; Christie, 1951). Kranck (1939a and b) considers 'trap' dykes at the Strait of Belle Isle as belonging to the same magmatic series as the basalt sheets. Similar basalts occur in the Cloud Hills of Northern Newfoundland. Clifford and Baird (1962) believe that the basalts of the Cloud Hills are possibly the effusive equivalents of the post-kinematic diabase dyke swarm of the plutonic core of the Great Northern Peninsula of Newfoundland. They state that these dykes have not been reported cutting the Paleozoic envelope. In a recent paper, Clifford (1965) concludes that the basalts are post-Lower Cambrian, and puts the youngest age limit as 334 m.y. based on a K/Ar whole rock age determination. Clifford and Baird's (1962) description of the Newfoundland diabase dykes corresponds closely to those of the giant St.Augustin gabbro dyke.

Fairburn et al (1966) present Rb/Sr whole rock ages on three volcanic groups which underlie fossiliferous Lower Cambrian in Southern Newfoundland, Cape Breton Island, and New Brunswick. The three dates, 495 ± 48 m.y. (Coldbrook, New Brunswick), 509 ± 40 m.y. (Fourdui, Cape Breton Island), and 494 ± 30 m.y. (Bull Arm, Newfoundland), are lower than expected for the Lower Cambrian, and it is suggested that the diffusion of Rb is responsible. It is interesting that the ages of the volcanics and the giant dyke are within experimental limits of each other so the possibility that they are of equivalent age cannot be excluded. Possibly related to these dykes is the anorthosite of Newfoundland described by Riley (1962) which has an age of 451 m.y.

The author concludes that the giant gabbro dyke of St.Augustin is related to the dykes and flood basalts of the Strait of Belle Isle and belongs to a period of basic igneous activity common to the whole Maritime region in the Early Paleozoic.

LAYERED METAMORPHIC ROCKS

Mapping gneissic terrain in the Grenville A subprovince is complicated by the closely spaced layering and great variation in composition of the rocks. In well-exposed areas like that of Mutton Bay the complexity of the geology is readily appreciated.

The mappable units chosen were first those that are relatively rare, have distinct compositions, and act as excellent marker horizons, such as quartzites, calc-silicate rocks and amphibolites. Quartzites and calc-silicate rocks are generally narrow layers and in many cases are exaggerated on the map. Grey garnetiferous-biotite-plagioclase gneiss and dark grey biotite-hornblende gneiss are easily recognized in the field and form distinct mappable units. Most of the gneisses fall into one of three units : pink granite gneiss ; green pyroxene-plagioclase gneiss ; and light grey plagioclase gneiss. However, rocks gradational between these are found. Finally, mixed units are recognized which either consist of two main components or three or more components. The latter as a rule contain paragneisses in addition to other types already mentioned. These paragneisses are generally too variable in composition and mineralogy to map separately.

Gneisses

Fine- to medium-grained pink granitic gneisses

There are essentially two types of pink granitic gneiss. One is a well foliated medium-grained variety found closely associated with the green pyroxene-plagioclase gneiss, and the other a fine-grained, weakly foliated variety found throughout the area. As the two varieties are not easily separated in the field they have been mapped as one unit.

Both varieties consist essentially of potash felspar, plagioclase, and quartz. The mafic content is low in the fine-grained variety but small red garnet porphyroblasts are a common accessory. In the well foliated variety about 5 percent biotite and/or hornblende is present. The range in mineral composition of the two varieties is given in Table III, Nos.1 and 2.

Fine- to medium-grained pink granitic gneiss is present throughout the area as a major constituent of all the mixed zones, occurring as conformable layers 6 inches to more than 100 feet thick. Contacts are generally sharp, but there are gradations into the fine-grained grey plagioclase gneiss with which it forms thick closely banded units. Potash felspar gives the rock its pale red colour which is preserved on the weathered surface, making the rock a conspicuous field unit. Foliation is weak but a faint banding conformable with the contacts and resulting from variations in composition and grain size (fig.3) is usually present, particularly on fresh surfaces. Mafics show strong preferred orientation and felspar and quartz show flattening parallel to the foliation and varying degrees of segregation into layers.

Well foliated, medium- to coarse-grained pink granitic gneiss is closely associated and interlayered with the green gneisses. There is often a subtle gradation into the latter in marked contrast to the fine-grained variety with its sharp contacts (fig.4). The colour is essentially pale red to pinkish grey but many varieties are moderate yellowish brown, and others contain a little pale olive plagioclase. The most characteristic feature of the rock is its

Table III

Estimated Range in Mineral Composition - Gneisses

	1	2	3	4
	Vol.%	Vol.%	Vol.%	Vol.%
Plagioclase	5 - 30	10 - 55	30 - 80	25 - 50
	An_{15-32}	An_{16-33}	An_{22-42}	An_{22-35}
	$An_{23.83}$(av.)	$An_{25.68}$(av.)	$An_{31.77}$(av.)	$An_{29.5}$(av.)
	+ albite	+ albite		+ albite
Potash felspar (+ perthite)	30 - 60	20 - 50	5 - 30	Tr. - 50
Quartz	20 - 50	10 - 50	5 - 30	15 - 35
Pyroxene	-	-	Tr. - 10	-
Hornblende	0 - 1	0 - 5	0 - 1	-
Biotite	Tr. - 10	0 - 5	Tr. - 10	Tr. - 15
Garnet	0 - 2	-	-	1 - 5
Opaques	Tr. - 3	Tr. - 3	Tr. - 3	Tr.
Sillimanite	-	-	-	0 - 5
Zircon	Tr.	Tr.	Tr.	Tr.
Apatite	Tr.	Tr.	Tr.	Tr.
Chlorite/ serpentine, etc.	0 - 2	0 - 2	0 - 5	Tr.
Carbonate	0 - Tr.	0 - Tr.	0 - Tr.	-
Sphene	0 - 1	0 - Tr.	0 - Tr.	-
Epidote	-	-	0 - Tr.	-
Sericite	Tr.	Tr.	Tr.	Tr.
Leucoxene	Tr.	-	0 - Tr.	-

1. Fine-grained pink granite gneiss (10 thin sections)
2. Medium-grained well-foliated pink granite gneiss (11 thin sections)
3. Green pyroxene-plagioclase gneiss (11 thin sections)
4. Grey garnet-(sillimanite)-biotite gneiss (5 thin sections)

Each of the above show the ranges in percent of minerals present in several thin sections. Percentages are visual estimates only.

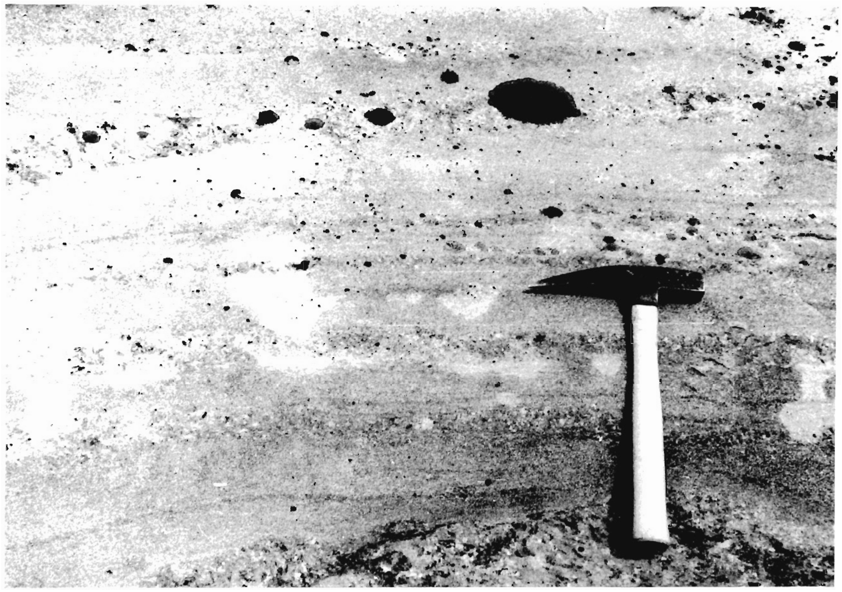


Fig. 3 - Fine-grained pink granitic gneiss displaying bands of different colour and grain size.

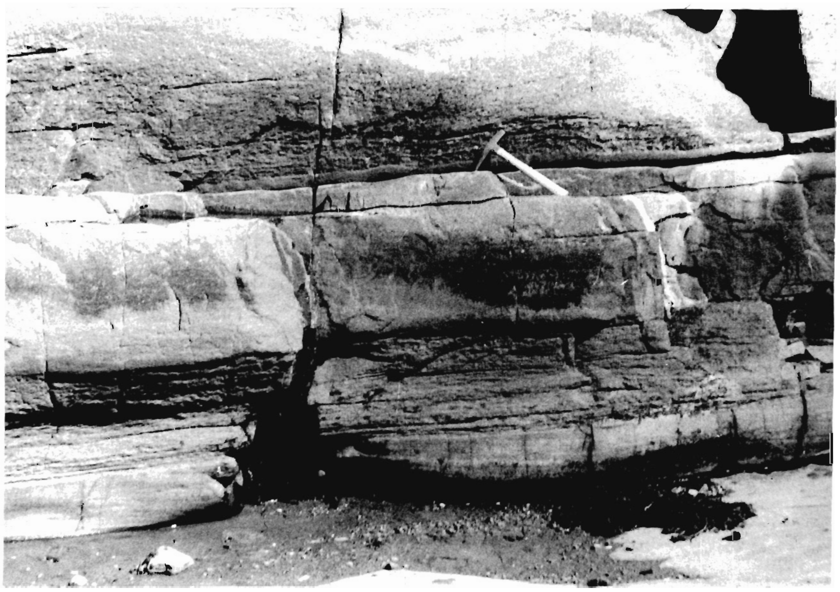


Fig. 4 - Fine-grained layered pink granitic gneiss (light) interlayered with green pyroxene-plagioclase gneiss (dark).

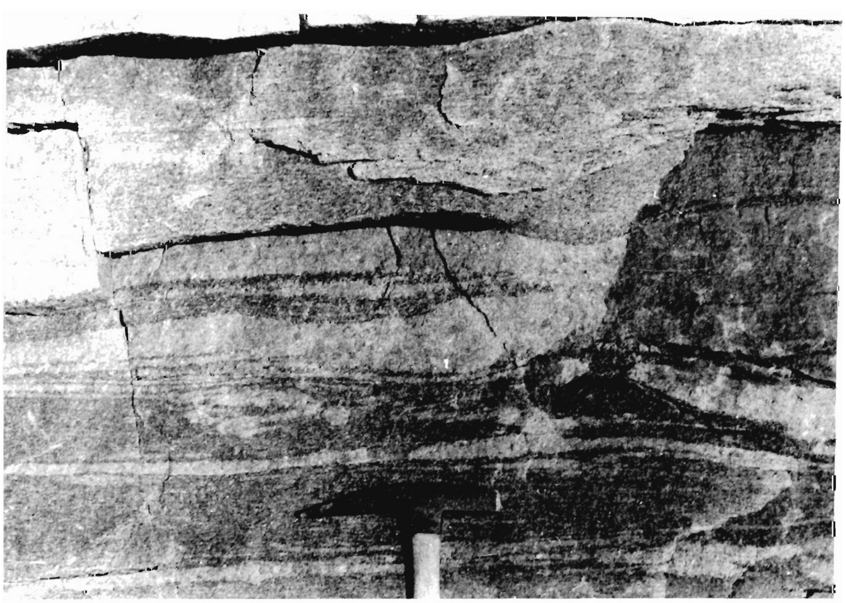


Fig. 5 - Dark grey biotite-hornblende gneiss (dark) intruded parallel to its foliation by granite (light), and displaying pinch and swell structure.

well-developed foliation, in which the mafic constituents are concentrated as thin folia about 1/4 inch apart between granular layers of quartz and felspar. In low mafic varieties the foliation is marked by segregation of quartz and felspar, and in some cases there is a tendency towards the development of an augen structure. Linear orientation of mafics and quartz-felspar aggregates is well-developed.

Green pyroxene-plagioclase gneiss

Most varieties of the green gneiss are medium-grained, pale olive, and are composed essentially of pale olive plagioclase with lesser amounts of quartz and potash felspar. All contain pyroxene with hornblende and/or biotite. Either ortho- or clino-pyroxene or both may be present but sphene occurs in rocks containing only clinopyroxene. Garnetiferous varieties are common west of Mutton Bay and cordierite with biotite and hypersthene is rare. The composition is granodioritic to quartz-dioritic and the range in mineral composition is given in Table III, No.3 (p.21).

Foliation is well-developed and is similar to that of the well foliated pink granitic gneiss. Linear orientation of quartz-felspar aggregates and mafic minerals, particularly biotite, on foliation planes is also pronounced.

Weathering is generally deep and only along shorelines was the gneiss readily recognizable by its green colour. Elsewhere it is a moderate yellowish brown to greyish orange and generally friable. The deep weathering of this gneiss probably causes it to be poorly exposed with respect to interlayered bands of more resistant granitic rocks.

The green coloration of the plagioclase is apparently related to the presence of amphibole and/or pyroxene (probably their alteration) as it is absent in the garnetiferous gneisses described below which are devoid of these minerals. Guy-Bray (1961), from a study of the green coloration, concluded that it was due to the presence of chlorite films along fractures and cleavages in the plagioclase.

Grey garnetiferous-biotite-plagioclase gneisses

Grey garnetiferous-biotite-plagioclase gneiss occurs as relatively narrow layers in zones of mixed gneisses, but it was mapped as a separate unit in some places where it acts as a characteristic marker horizon. Essential minerals are plagioclase and quartz, with lesser amounts of biotite, garnet, and potash felspar. The range in mineral composition is given in Table III, No.4 (p.21).

The rock is medium-grained, light to medium light grey and pinkish grey, and well foliated, with biotite segregated into thin folia 1/8 to 1/4 inch apart. Fine sillimanite needles are occasionally present and, together with the biotite, exhibit a strong lineation. Red garnet porphyroblasts up to an inch in diameter are characteristic and generally constitute no more than 5 percent, but locally as much as 20 percent, of the rock. Crystals are fractured and poikilitic and occur singly or as masses flattened parallel to the foliation. The garnets occur both in the gneiss and in associated concordant quartz-felspathic bands or veins. In none of these rocks does the plagioclase exhibit a green coloration.

Sillimanite-biotite-garnet gneiss

Included in the mixed gneisses

are zones of massive, medium- to coarse-grained, garnetiferous, quartz-felspathic material in which occur easily weathered layers or lenses, a fraction to 2-3 inches wide, of sillimanite, biotite, and garnet. The zones are nowhere greater than 100 feet wide and do not constitute mappable units but are conspicuous and serve as excellent marker horizons.

Sillimanite occurs as prisms varying in size from minute needles to crystals 1 inch long and 1/8 inch wide, and, with the intimately mixed biotite, produces a pronounced lineation. Masses of small garnet crystals may occur elongated in the direction of the lineation.

Light grey plagioclase gneiss

Light grey fine- to medium-grained plagioclase gneiss is composed essentially of plagioclase and quartz with varying amounts of potash felspar. Mafics include biotite and hornblende with pyroxene in low potash felspar varieties. It is similar in appearance to the fine-grained pink granitic gneiss with which it is often associated. The range in mineral composition is given in Table IV, No.1.

Dark grey biotite-hornblende gneiss

Dark grey biotite-hornblende gneiss is best exposed in the neighbourhood of Île aux Graines. It is fine- to medium-grained, medium dark grey to olive black, and composed essentially of plagioclase, biotite, hornblende, and opaque minerals, with considerable potash felspar in the pink varieties. The range of mineral composition is given in Table IV, No.2.

Table IV

Estimated Range in Mineral Composition

Gneisses, porphyritic granite, and granodiorite

	1	2	3	4
	Vol.%	Vol.%	Vol.%	Vol.%
Plagioclase + alteration products	50 - 60 An_{28-38} $An_{33.17}$(av.)	35 - 55 An_{27-29} An_{28}(av.)	5 - 25 An_{25-32} An_{29}(av.) + albite	25 - 65 An_{25-34} $An_{30.57}$(av.)
Potash felspar	Tr. - 5	10 - 30	40 - 60	10 - 40
Quartz	25 - 40	5 - 25	20 - 50	10 - 25
Pyroxene	0 - 5	-	-	-
Hornblende	0 - 1	5 - 25	0 - 3	2 - 20
Biotite	2 - 3	1 - 5	Tr.- 5	Tr. - 10
Opaques	1 - 3	3 - 5	Tr.- 3	1 - 7
Zircon	Tr.	Tr.	Tr.	0 - Tr.
Apatite	Tr.	Tr.- 3	Tr.	Tr. - 1
Chlorite	0 - Tr.	-	Tr.- 1	0 - Tr.
Carbonate	0 - Tr.	-	-	0 - Tr.
Sphene	0 - Tr.	0 - Tr.	Tr.	0 - Tr.
Sericite	Tr.	Tr.	Tr.	Tr.

1. Light grey plagioclase gneiss (3 thin sections)
2. Dark grey biotite-hornblende gneiss (3 thin sections)
3. Coarse-grained porphyritic granite (5 thin sections)
4. Coarse-grained porphyritic granodiorite (7 thin sections)

Each of the above show the ranges in percent of minerals present in several thin sections. Percentages are visual estimates only.

The dark colour and its relative homogeneity make this unit conspicuous, particularly along the coast where it serves as an excellent marker horizon. Fig.5 (p.22) shows the unit cut by granite. Foliation and linear orientation of biotite and hornblende is well-developed.

Mixed gneisses

Various combinations of rock types constitute the mixed units mapped. Two mixed units are composed of pink granitic gneiss and green pyroxene-plagioclase gneiss, with one or other dominant. Two units consist of light grey plagioclase gneiss in subordinate amounts with either pink granitic gneiss or green pyroxene-plagioclase gneiss. A fifth unit is the most diverse, consisting of three or more main rock types, including all the gneisses except the green pyroxene-plagioclase gneiss and the well foliated granitic gneiss, and including the paragneisses and the porphyritic granite and granodiorite described below.

Quartzites

Quartzites outcrop as layers generally less than 50 feet thick but layers of greater thickness were observed in **Anse de l'Argile** on Petit Rigolet. Several were traced over a mile as they are well-jointed and form prominant cliffs (fig.6).

Most quartzites consist of pure, glassy white to very light grey and light olive recrystallized quartz, and in some cases contain conspicuous amounts of microcline, garnet, and sillimanite. They exhibit layering or bedding which in some cases results from the segregation of microcline, the presence of garnet-rich layers, or of sillimanite needles along certain planes, but in most cases from the difference in colour of the quartz and the presence of

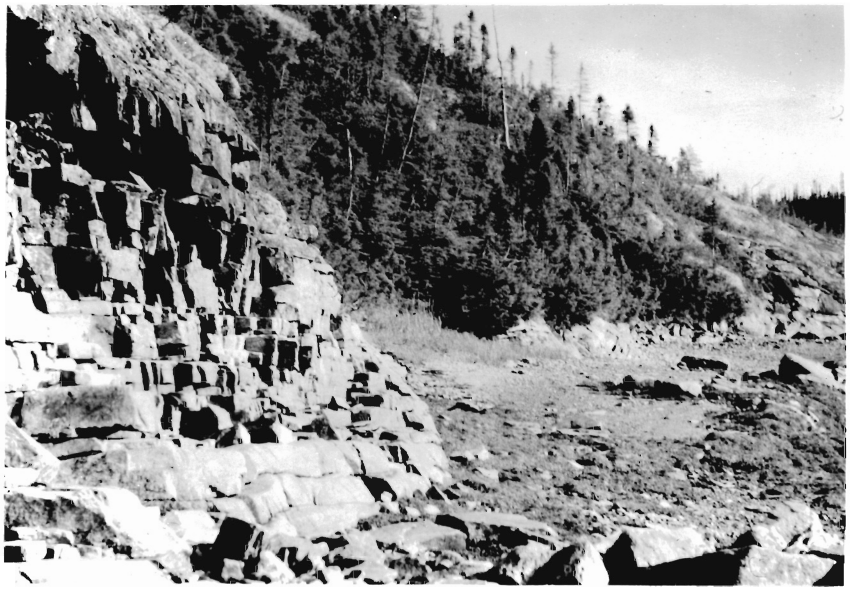


Fig. 6 - Well-developed jointing in nearly horizontal bedded quartzite forming a cliff. Anse de l'Argile.

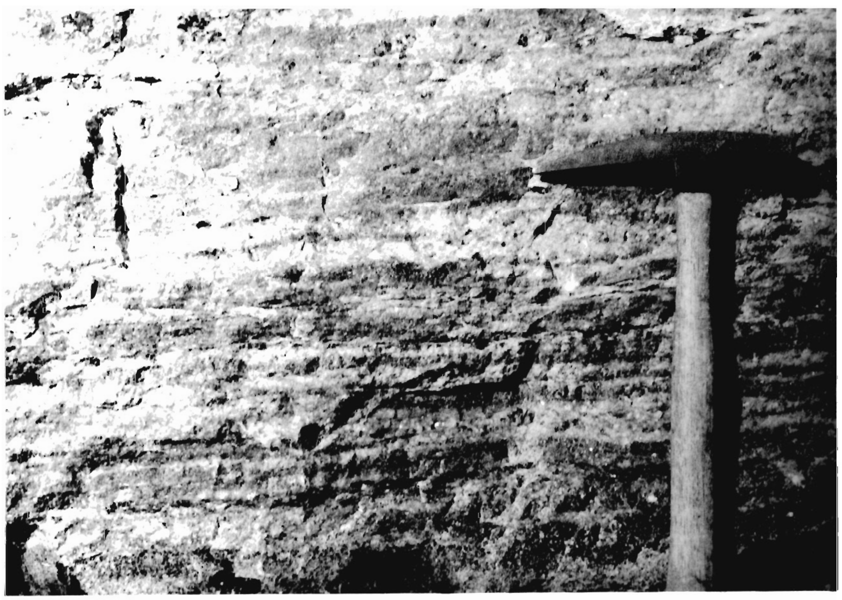


Fig. 7 - Layered or bedded garnetiferous quartzite with sillimanite concentrated in narrow dark streaks parallel to the layering.

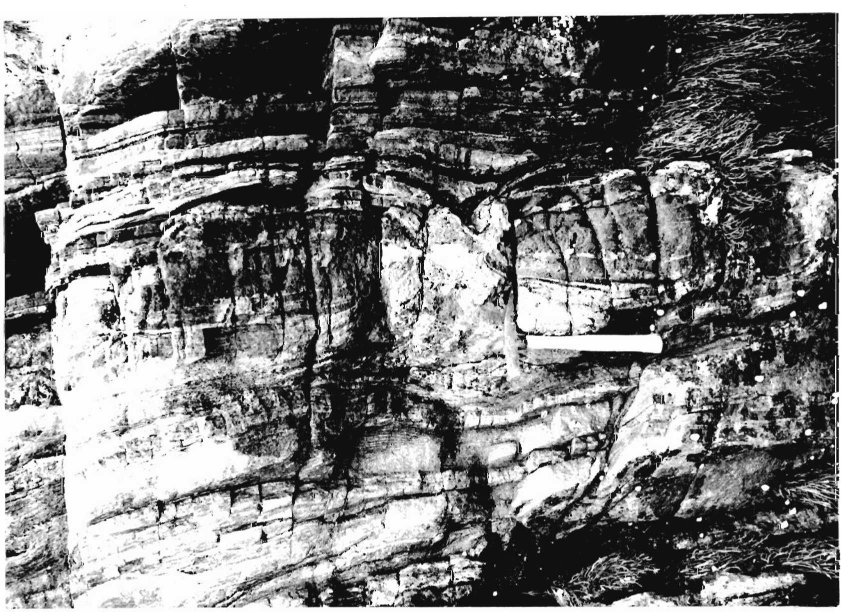


Fig. 8 - Closely layered calc-silicate rocks with well-developed boudinage.

minor amounts of mica and black opaque minerals (fig.7, p.28).

Many narrow layers (4-5 feet) might conceivably be veins but banding in the thicker layers is most certainly bedding. Diagnostic sedimentary features such as ripple marks were not observed but the regular width, continuity, and concordant contacts with the gneisses supports a sedimentary origin.

Calc-silicate Rocks

Calc-silicate rocks are limited in occurrence and are exposed on shorelines as easily weathered layers generally less than 20 feet thick. They are well-layered, varying in thickness from a fraction of an inch to several feet (fig.8, p.28), and layering is enhanced by differential weathering.

Layers are composed of combinations of calcite, diopside, scapolite, biotite, quartz, potash felspar, and wollastonite. The most common associations are scapolite-diopside, usually but by no means always with scapolite predominant, scapolite-biotite, quartz-scapolite-diopside, calcite-diopside-scapolite, calcite-diopside-microcline, and wollastonite-scapolite-diopside. Sphene is a common accessory, and pyrite, fluorite, and traces of chalcopyrite and graphite were observed in some specimens. Calcite layers are generally 1-12 inches wide and zones rich in calcite have been the most intensely folded, the formation of boudins being common.

Amphibolites

Amphibolites are of more than one age and possibly of more than one origin. Some have been involved in the folding and complete regional metamorphic history, as sills, volcanic flows, or calcareous sediments. Others were injected at a later stage and show little effect of folding. Amphibolites grade into meta-gabbros and, since many of the amphibolites are igneous and no evidence of a sedimentary origin is found, all the amphibolites and meta-gabbros have been mapped and described together in a later section (p.42).

Mineralogy of gneisses and paragneisses

Quartz occurs both as irregular grains elongated parallel to the foliation, and as small rounded inclusions in the felspars, particularly the potash felspar. The small rounded inclusions are most conspicuous in the fine-grained pink granitic gneisses, and may represent original detrital grains or perhaps an earlier smaller grain size, the small grains having been isolated in the felspars during grain growth. On the other hand, they may be a feature similar to myrmekite common in those rocks where plagioclase abuts on potash felspar. The quartz is invariably strained with undulating extinction.

Plagioclase is oligoclase-andesine (An_{26-42}) and in the granitic varieties tends to be more sodic (21 thin sections averaging $An_{24.8}$) than in the granodioritic varieties (22 thin sections averaging $An_{31.2}$). Crystals are anhedral, unzoned, and exhibit polysynthetic twinning (mostly albite) with associated pericline twinning. Twin lamellae often wedge out near grain boundaries. Many twins are bent and the grains fractured, indicating deformation.

Alteration of oligoclase to albite and sericite is a conspicuous feature of the granitic varieties (fig.9). The alteration is irregular, occurring as patches and along cleavages in the clear oligoclase, and selectively replacing certain twin lamellae. Twinning in the albite is pronounced and is continuous with that of the poorly

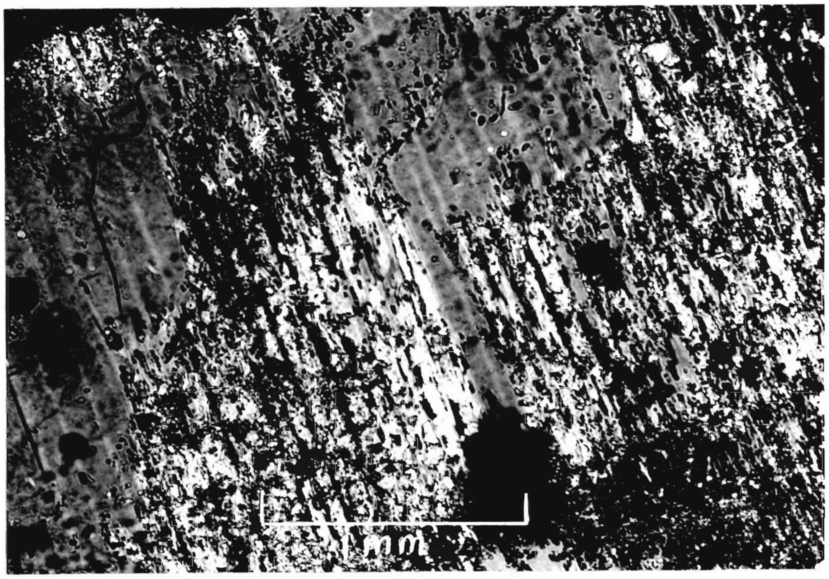


Fig. 9 - Alteration of oligoclase (clear, grey, poorly twinned) to albite (black and white twin lamellae) and sericite. Crossed nicols. X 35.

Fig. 10 - Apophysis of green pyroxene-plagioclase gneiss cutting medium-grained pink granitic gneiss.

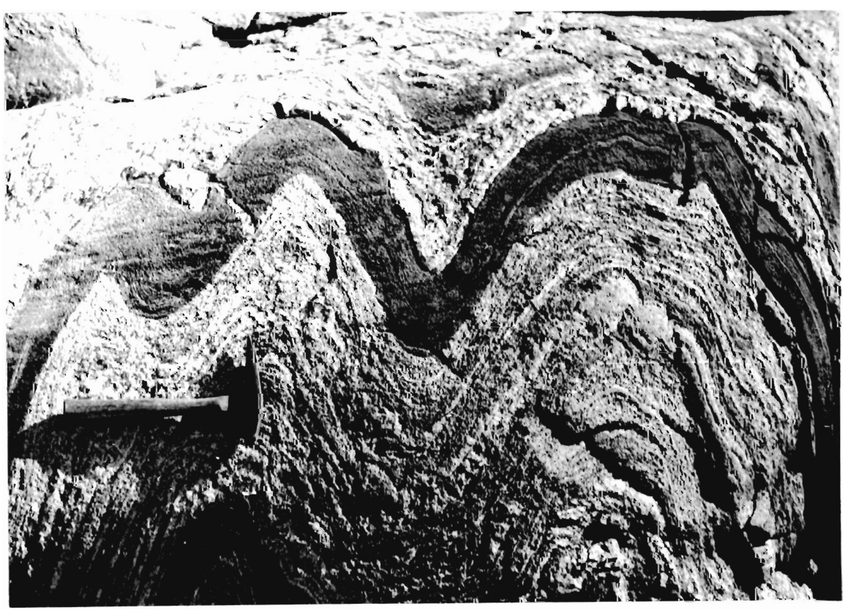


Fig. 11 - Concordant amphibolite layer in folded green pyroxene-plagioclase gneiss.

twinned oligoclase. The more calcic andesine of the granodioritic gneisses exhibits slight sericitization but albite is lacking. One fine-grained pink granitic gneiss, by no means abundant in the area and characterized by its distinct pale red colour, contains clear unaltered sodic oligoclase (An_{12}).

Potash felspar is mostly anhedral twinned microcline perthite with the perthitic plagioclase occurring as veins, rods, or patches. It is unaltered and appears to be later than the plagioclase and quartz.

Biotite is the main mafic constituent and is black with very pale orange to moderate brown and dark reddish brown pleochroism, except in the calc-silicate rocks where it is light brown and slightly pleochroic from colourless to very pale orange. Flakes are subhedral and generally undeformed, but occasionally bent flakes are encountered. It exhibits a strong preferred orientation and is the most important element of the foliation and lineation of the gneisses and paragneisses. Biotite occurs as an alteration product of the hornblende and as reaction rims around black opaques. Slight alteration to chlorite is common.

Hornblende is a constituent of all the gneisses except the garnetiferous and most of the pyroxene-plagioclase ones, and is rare in the fine-grained pink varieties. It is anhedral and alteration to pseudomorphous masses composed of biotite, chlorite, opaques, and carbonate is common. It is pleochroic in greens and browns, and in 7 thin sections has the following range of optical properties : $z \wedge C = 13\text{-}17^{\circ}$, $2V_x = 44\text{-}74^{\circ}$.

Pyroxene is present in the green pyroxene-plagioclase gneiss and in possibly related fine-grained grey gneisses. Clino- and ortho-pyroxene occur either co-existing or alone as anhedral to subhedral stubby crystals. Hypersthene is the more common and is strongly pleochroic from very pale orange to very pale green. Clinopyroxene is very pale green and weakly pleochroic, forming partial rims around the hypersthene when the two occur together. Clinopyroxene is a major constituent in the calc-silicate rocks where it is greyish olive green in hand specimens, and occurs as subhedral to anhedral crystals occasionally up to an inch or more in length. In thin section it is slightly pleochroic, varying from light green to pale green to colourless. Clinopyroxenes in 5 thin sections of calc-silicate rocks and 4 thin sections of green pyroxene-plagioclase gneisses have optical properties within the range $2V_z = 50\text{-}64^\circ$, $z \wedge c = 40\text{-}46^\circ$.

Garnet is the characteristic mineral in the grey garnet-biotite-plagioclase and sillimanite-biotite-garnet gneisses and is a conspicuous minor constituent in some zones of the fine-grained pink granitic gneisses. It is not found with hornblende but occurs with hypersthene in some green gneisses west of Mutton Bay. Porphyroblasts are subhedral to euhedral, generally small, but sometimes an inch in diameter, and often fractured and poikilitic. In most cases they occur as clusters rather than single grains. The colour is generally pale red purple to greyish red purple in hand specimens and in thin section it is very pale orange.

Sillimanite, when present, occurs as euhedral prisms varying in size from fine needles to crystals 1 inch long and 1/8 inch wide and exhibits an excellent preferred orientation.

Cordierite occurs with hypersthene and biotite in green pyroxene-plagioclase gneiss around Baie Querry and on the islands west of Mutton Bay. It is pale blue and glassy and could easily be overlooked.

Scapolite, a common constituent of the calc-silicate rocks, is white in hand specimen and colourless in thin section. It is the calcium-rich variety with indices of refraction N_O 1.590 $\pm$ .003 and N_E 1.560 $\pm$ .003 corresponding to a composition 70-75 percent $Ca_4Al_6Si_6O_{24}CO_3$ (meionite) (Winchell and Winchell, 1959, p.353).

Calcite constitutes the thin carbonate bands and is an important constituent of the calc-silicate bands.

Wollastonite occurs as white tabular crystals in some calc-silicate rocks. Crystals up to 6 inches long are found in Baie des Oies where it is associated with quartz.

Accessory minerals include euhedral prisms of apatite, euhedral but rounded crystals of zircon, and irregular grains of opaque iron ores generally magnetite with exsolved laths of ilmenite. Dark yellowish green spinel is intergrown with black opaques in a garnet-biotite-plagioclase gneiss. Sphene is associated with black opaques as masses of irregular grains and does not occur with orthopyroxene, and in the calc-silicate rocks is strongly pleochroic in browns. Chlorite, sericite, carbonate, leucoxene, and serpentine are common alteration minerals.

Metamorphism

Green pyroxene-plagioclase gneisses and amphibolites belong to the amphibolite and the granulite facies of Eskola (1939). The remaining gneisses and calc-silicate rocks could belong to either of the above facies as their mineral assemblages are common to both facies.

Amphibole and/or biotite is invariably present in the rocks of the granulite facies, confining them to the hornblende granulite subfacies of Turner (1958). Turner and Verhoogen (1960) put the granulite facies temperatures between 700°C and 800°C. De Waard has recently (1965) proposed a six-fold subdivision of the granulite facies based upon variable P_{load}-P_w-T conditions. Garnet and cordierite isograds subdivide both the pyroxene and the hornblende-granulite subfacies. In the Mutton Bay area cordierite is relatively rare but was seen in the field west of Mutton Bay and around Baie Querry where it accompanies orthopyroxene, biotite, plagioclase, and quartz. Garnetiferous green pyroxene-plagioclase gneisses are rare. Garnets occurring together with orthopyroxene show no reaction relationship that might indicate the presence of De Waard's hornblende - clinopyroxene - almandine subfacies. All the Mutton Bay granulites belong to his hornblende - orthopyroxene - plagioclase or biotite - cordierite - almandine subfacies, suggesting a moderate to low load pressure and moderate water pressure (De Waard, 1965). The cordierite-bearing rocks are fairly high in the local stratigraphy where load pressure might be at a minimum, but there are not enough occurrences to establish this relation.

Miyashiro (1961) introduced the concept of metamorphic facies series and showed that each individual metamorphic area is characterized by a definite facies series which can be represented by a curve in a temperature pressure diagram. He contrasted the high pressure facies series of the Grampian Highlands with a low pressure facies series of the Abukuma Plateau of Japan. Winkler (1965) uses the terms Barrovian-type and Abukuma-type for these two facies series respectively. In the amphibolite facies it is possible to differentiate, in the case of basic rocks, between these two facies series, since almandine does not occur in the basic rocks of the Abukuma-type. Mutton Bay amphibolites, which belong mostly to the amphibolite facies, are Abukuma-type. Garnets are lacking except in a few rare cases at contacts.

Mineral assemblages in gneisses other than the green pyroxene-plagioclase gneisses are similar both in the amphibolite and the granulite facies. Muscovite and epidote are absent from the regionally metamorphosed rocks which shows that the lowest 'grade' of metamorphism could be that of Turner and Verhoogen's (1960) sillimanite - almandine - orthoclase subfacies of the amphibolite facies. Sillimanite is the only aluminous silicate present. According to Winkler (1965, p.95) this subfacies would commence around 680°-$700^{\circ}C$ (above 2000 bars P_{H_2O}).

Lime silicate rocks contain assemblages found in the amphibolite and granulite facies. The occurrence of wollastonite is important as it is generally found in the highest part of the amphibolite facies under conditions of Abukuma-type metamorphism. Wollastonite occurs in Barrovian-type metamorphism in Idaho (Hietanen, 1967) and at Nanga Parbat, Northwest Himalayas (Misch, 1964). A low partial pressure of CO_2 is essential for the formation of wollastonite under Barrovian-type metamorphic conditions. In the Idaho rocks the reaction $CaCO_3 + SiO_2 \longrightarrow CaSiO_3 + CO_2$ is incomplete, and the calc-silicate layers in which the wollastonite formed at

Nanga Parbat are believed to be open systems to CO_2. Winkler (1965) suggests that their small thickness (few cms.) would allow dilution of CO_2. There is no reason to believe that the partial pressure of CO_2 was low in the Mutton Bay rocks and these rocks probably formed under Abukuma-type metamorphic conditions.

Isograds between De Waard's (1965) hornblende - orthopyroxene - plagioclase subfacies of the granulite facies and the amphibolite facies could not be drawn at the scale of mapping because of the apparent interlayering of the two facies. Buddington (1963) believes that rocks of his Adirondack area have been impermeable to either access or to loss of H_2O during plastic flow and any subsequent metamorphism, and this is probably the case at Mutton Bay. The observed differences in facies is not attributable to difference in temperature but to difference in fugacity of water. H_2O set free from hornblende might not escape and the build-up in pressure would preserve the remaining hornblende.

Miyashiro (1961) noted that the mineral assemblages found in the Grenville Province are those characteristic of the Abukuma and Buchan types. The latter is considered intermediate in character between the Abukuma and Barrovian types and is characterized by the presence of staurolite which however is not found at Mutton Bay. Mutton Bay rocks of both the amphibolite and granulite facies are low pressure assemblages. The pressure for the upper amphibolite facies in Abukuma-type metamorphism is estimated by Winkler (1965) to be 2000 - 3000 bars and by Hietanen (1967) to be about 3500 bars. These pressures correspond to depths of 7-12 km. Temperatures of metamorphism of the Mutton Bay rocks are estimated as 680°-750°C.

Origin of the Gneisses

High metamorphic grade and intense deformation has left little evidence of the original nature of the rocks. All the gneisses exhibit a concordant compositional layering. Layering is generally closely spaced and regular over considerable distances, and even the granitic gneisses are layered, with layers differing slightly in composition and grain size. Layering in the gneisses conforms with the few narrow layers of meta-sediments such as quartzites and calc-silicate rocks.

Cutting relations occur between some gneisses, but in most cases this can be ascribed to remobilization. In the calc-silicate horizons certain layers rich in calcite are very mobile and fill fractures but there is no doubt that intrusion in this case could have taken place in the solid state. Green pyroxene-plagioclase gneiss in one case was observed cutting medium-grained pink granitic gneiss (fig.10, p.31), and is significant because it offers the only real evidence of an igneous origin for the green pyroxene-plagioclase gneisses. The green pyroxene-plagioclase gneiss in this case is close to the contact with the coarse-grained porphyritic granite, and it is possible that intrusion of the granite caused or increased anatexis in the adjacent green pyroxene-plagioclase gneisses. The Île Lecouvre intrusion which is probably related to the porphyritic granite is surrounded by massive green rocks which intrude the country rock.

The quartzites, calc-silicates, and garnet-(sillimanite)-biotite gneisses are accepted meta-sedimentary rocks. They are narrow bands generally less than 100 feet thick and constitute an extremely small part of the total rock mass, but they are continuous, distributed throughout the succession, and are relatively undisturbed, suggesting that they are a closely related part of the gneissic succession.

There is no difficulty in finding possible original materials for the majority of gneisses and they could be derived from sediments and volcanics with some intrusive sills. Most of the gneisses are believed by the author to represent graywackes and shales. Whatever the original composition, and without clear evidence to the contrary, the gneissic sequence must for practical purposes be treated as a layered sequence.

Stratigraphy of the Gneisses

Cross-sections through the gneisses (in back pocket) show an intruding granite diapir (dome) pushing westward and folding the gneisses ahead of it. The rocks behaved plastically with deformation much like that in the pressure box experiments of Willis (1893) (See Billings, 1960, p.22).

In spite of the folding it is possible to get an idea of the thickness of the gneiss exposed in the area by measuring the less intensely folded parts of the section. Assuming that the structural interpretation of the St.Augustin sheet is correct, a minimum total thickness of gneisses exposed above the granite in this part of the area is in the order of 30,000 feet. A minimum thickness of about 18,000 feet is exposed in the western part of the area.

The stratigraphy of the rocks exposed in the Mutton Bay area can be seen in the cross-sections. The lower units, strongly intruded by granite, are mixed gneisses, mostly metamorphosed sediments including many pure quartzites. These are overlain by pink granitic gneisses alternating with green pyroxene-plagioclase gneisses both believed by the author to be paragneisses representing shales and graywackes. Occasional pure quartzites and lime-rich sediments occur throughout this sequence. A change in conditions at the top of the sequence is suggested by the grey biotite gneiss but its composition is much the same as the green pyroxene-plagioclase gneiss.

The Wakeham series of sandstones, quartzites, and schists overlies gneisses like those of Mutton Bay. Coarse-grained porphyritic granite extends west along the coast to within 50 miles of outcrops of the Wakeham series (Longley, 1944a), and if the granite remains concordant with the gneisses, as appears in the Mutton Bay area, then the gneisses below the Wakeham series can be correlated with those of the Mutton Bay area, and the Wakeham series would form the top of the sequence. The Wakeham sedimentary series has been folded about a N-S axis and in this series the lack of cross-folding common in the Mutton Bay gneisses is explained by the brittle nature of the quartzites which tend to fracture rather than refold. The brittle nature of the quartzites is supported by the abundance of gabbro intrusions in the quartzites.

Depth of Burial of the Gneisses

Grenier (1957, p.28-29) estimates the minimum thickness of the Wakeham group of sediments as 25,000 feet. Metamorphic grade is that of the epidote-amphibolite facies. The granites intruding the Wakeham series are more cross-cutting than those in the gneisses but have still pushed aside the overlying beds in a diapiric fashion. They are mesozonal in contrast to those cutting the Mutton Bay group which are catazonal.

If the minimum thickness of the Wakeham series is added to the minimum thickness of the Mutton Bay group, a total thickness of sediments of 55,000 feet (or about 10 miles or 16 km) is obtained which is of geosynclinal dimensions. It must be remembered that the thickness may not be that of the layers as originally deposited, as folding can both increase and decrease the thickness of a layer. The depth of burial indicated by the metamorphic facies is 7-11 km which suggests that folding and erosion raised the gneisses to shallower depths before the metamorphic facies was imprinted on the rocks.

Age of Deposition of the Gneisses

The Wakeham series has been correlated by Béland (1950) Grenier (1957), and Blais (1955) on the basis of similar composition, texture, degree of metamorphism and association with gabbro sills, with the rocks of the Labrador Trough which have K/Ar ages of 1500-1600 m.y. The Mutton Bay group of gneisses are apparently older than the Wakeham series and, if the correlation with the Labrador Trough is correct, the Mutton Bay gneisses represent sediments older than 1600 m.y.

EARLY METAMORPHOSED IGNEOUS ROCKS

The early metamorphosed igneous rocks have all been involved in the folding of the area and have structural elements concordant with those of the gneisses.

Meta-gabbros and Amphibolites

Meta-gabbros and amphibolites are mafic-rich rocks that have been metamorphosed and deformed, and are scattered across the area as dykes and sill-like bodies less than 1 foot (fig.11, p.31) to 700 feet wide. Contacts of the larger bodies are seldom exposed and only a few could be traced for more than half a mile.

Many are clearly of intrusive igneous origin (fig.12). Some amphibolites may represent volcanic flows or calcareous sediments, but no evidence was found to support either of these possibilities. Most are interlayered with the gneisses and have a good foliation and lineation, but some are discordant. Foliation is well-developed in the narrow bodies, along contacts, and in places that have suffered intense deformation, and foliated varieties generally have a high biotite content. Hornblende gives rise to a lineation rather than a foliation. Larger bodies are more massive and generally coarser grained away from the contacts. The rocks are folded together with the gneisses and many thin interlayered amphibolites are stretched into boudins (fig.13). A few small dykes have a foliation parallel to the host rock and oblique to the contacts.

The meta-gabbros and amphibolites are essentially hornblende-andesine rocks but several less-altered meta-gabbros contain pyroxene and labradorite away from the contacts. The labradorite crystals are unzoned and equidimensional, indicating recrystallization (fig.14).

Meta-gabbro

A good example of a meta-gabbro is a sill exposed for a 1/4 mile on the west side of Baie Querry. It is at least 55 feet

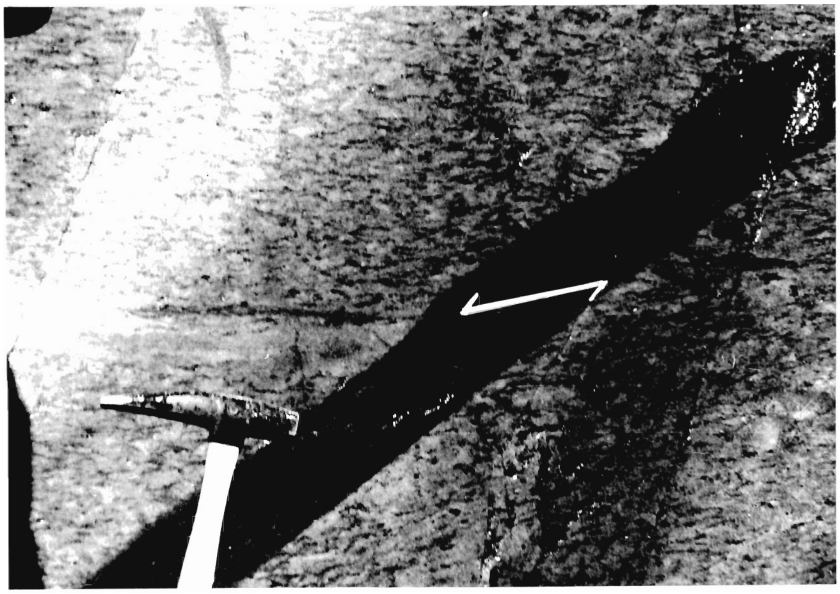


Fig. 12 - Amphibolite dyke cutting the foliation of coarse-grained pink granitic gneiss. Foliation in dyke is as shown.

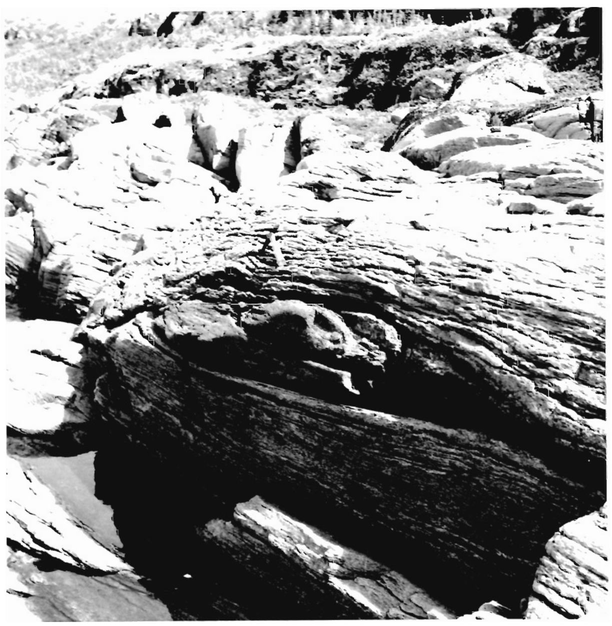


Fig. 13 - Lense or boudin of amphibolite resulting from the breaking up of a thin amphibolite layer in green pyroxene-plagioclase gneiss.

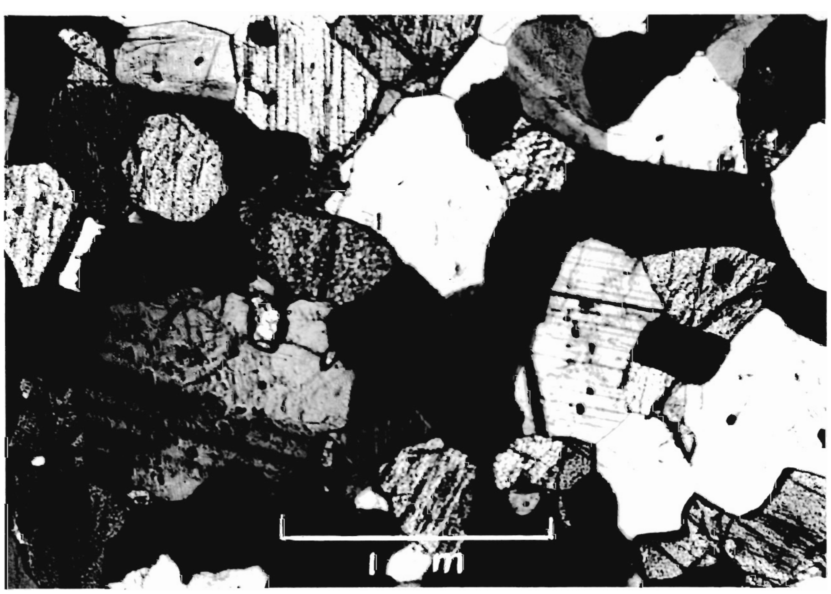


Fig. 14 - Meta-gabbro composed of equidimensional unzoned twinned labradorite (grey to white), pyroxene (grey frosted), pyrrhotite (black), and magnetite (black).
Crossed nicols. X 35.

thick, is layered as a result of magmatic differentiation and metamorphism, and the exposed contact is sharp (fig.15). Foliation, lineation, and axes of minor folds are parallel to those in the gneiss. Pyrrhotite-rich zones, 1-2½ feet wide and parallel to the foliation, are conspicuous. A continuous zone occurs 6 inches to 5 feet above the lower contact, and a second zone of disconnected pods occurs approximately 40 feet above the contact while small irregular masses occur throughout the sill. The grain size in general increases away from the contact.

The mineralized zones are medium-grained pyroxene-andesine rocks and the rest of the body is a recrystallized hornblende gabbro containing unzoned labradorite or bytownite (An_{70} the most calcic determined). The latter consists essentially of plagioclase, pyroxene, and hornblende, with minor amounts of opaques, spinel, and apatite, with sericite an alteration mineral. The estimated mineralogical composition of the meta-gabbro is given in Table V, No.1.

Both pleochroic hypersthene with $2V_x = 40-44^\circ$ and weakly pleochroic clinopyroxene with $2V_z = 56^\circ$ and $z \wedge C = 35^\circ$ are present. Hornblende is strongly pleochroic in browns and greens with optical properties in the range $2V_x = 68-80^\circ$ and $z \wedge C = 10-16^\circ$. Opaques, green spinel, and apatite are accessory minerals and sericite is a minor alteration mineral.

Amphibolites

Amphibolites are generally medium-grained olive black rocks with well-developed lineation due to the preferred orientation of the hornblende crystals. They consist essentially of andesine, hornblende, biotite, and opaque minerals with or without hypersthene

Fig. 15 - Lower contact of a concordant meta-gabbro (grey) in green pyroxene-plagioclase gneiss (white). A zone two feet above contact is rich in pyrrhotite. Baie Querry.

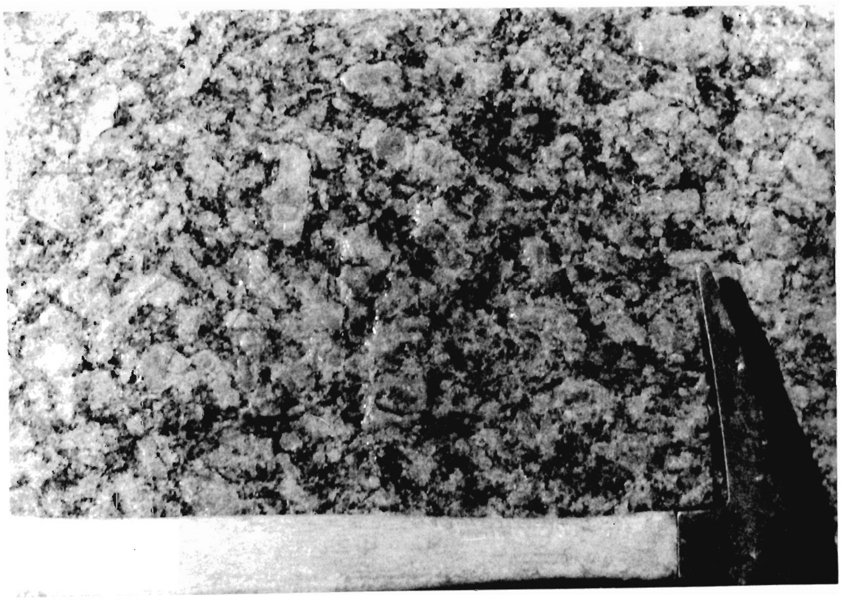


Fig. 16 - Coarse-grained pink porphyritic granite.

Fig. 17 - Coarse-grained grey granodiorite with large grey plagioclase phenocrysts (above hammer) outlined in black.

Table V

Estimated mineralogical composition - Meta-gabbro and amphibolite

	1	2	3	4	5
	Vol.%	Vol.%	Vol.%	Vol.%	Vol.%
Plagioclase	50	23	38	25	45
	An_{70} (max.)	An_{37-39}	An_{33-37}	An_{32}	An_{42-44}
Potash felspar	-	-	-	10	-
Pyroxene					
ortho-	20	16	-	-	-
clino-	10				
Hornblende	20	47	46	37	-
Biotite	-	5	15	20	40
Garnet	-	-	-	-	10
Quartz	-	-	-	Tr.	-
Opaques	Tr.	9	1	4	5
Spinel	Tr.	-	-	-	Tr.
Apatite	Tr.	Tr.	Tr.	2	Tr.
Sericite	Tr.	-	-	-	-
Chlorite	-	Tr.	-	-	-
Zircon	-	-	Tr.	-	Tr.
Sphene	-	-	-	2	-
		100	100	100	

1. Meta-gabbro
2. Hornblende-andesine gneiss - amphibolite
3. Hornblende-andesine gneiss - amphibolite
4. Hornblende- biotite-andesine gneiss
5. Biotite-garnet-andesine gneiss

No. 1 and 5 are visual estimates each on a single thin section. Nos. 2 to 4 are modal analyses on a single thin section counting 500-1000 points.

and with minor amounts of chlorite and apatite. The mineralogical composition of two thin sections is given in Table V, Nos.2 and 3 (p.46).

Plagioclase occurs as anhedral equidimensional grains generally interstitial to the ferromagnesian minerals and is a well-twinned and relatively unaltered andesine.

Hornblende is strongly pleochroic in browns and olive browns, and is anhedral containing inclusions of plagioclase and opaque minerals. Biotite is pleochroic from greyish orange to dark reddish brown and is an important constituent of the hornblende-biotite-andesine and biotite-garnet-andesine gneiss into which the amphibolites grade. Hypersthene is strongly pleochroic from colourless to very pale orange and occurs as anhedral grains generally interstitial to the hornblende.

Opaque minerals are associated with the other mafic constituents as fairly large irregular grains. Apatite is present as subhedral to euhedral crystals, and chlorite is a late alteration mineral.

Hornblende-biotite-andesine gneiss : Hornblende-biotite-andesine gneiss grades into and is similar in appearance to the amphibolites. It is composed essentially of andesine, potash felspar, hornblende, and biotite, with minor amounts of apatite, sphene, opaque minerals, and sericite. The mineralogical composition of a typical thin section is given in Table V, No.4 (p.46). The andesine is altered to sericite and potash felspar is perthitic and untwinned. The opaque minerals include sulphides and sphene, and the latter occurs as irregular grains and as rims around the iron ores.

Biotite-garnet-andesine gneiss : Biotite-garnet-andesine gneiss is relatively rare and forms a narrow zone, generally no more than 6 inches wide, at the contacts of some amphibolites. A thin section of a typical specimen contains andesine (An_{42-44}), pink garnet, biotite, and black opaques, with minor amounts of apatite, zircon, and spinel. An estimate of the mineralogical composition is given in Table V, No.5 (p.46). Foliation is well-developed with a preferred orientation of biotite flakes. Anhedral, fractured and poikilitic garnet porphyroblasts have both pushed aside and enclosed the biotite.

Age of the Meta-gabbros and Amphibolites

All the rocks discussed above are older than the regional metamorphism and the last phase of folding. Similar gabbros occur in abundance as sills and dykes in the Wakeham series of quartzites to the west where they are the oldest intrusives recognized (Grenier, 1957) and are cut by granite probably of equivalent age to the porphyritic granite of Mutton Bay. Some of the Mutton Bay amphibolites are definitely older than the porphyritic granites. The lesser abundance of gabbro in the Mutton Bay area may be due to the greater incompetence of the intruded rocks and the deeper level of intrusion as the Wakeham series appears to lie stratigraphically above the Mutton Bay gneisses.

Porphyritic Granite and Granodiorite

Porphyritic granite and granodiorite covers large parts of the area. Generally one grades into the other but where sharp contacts were observed granite cuts granodiorite. Granodiorite dominates in narrow layers within the gneisses while granite dominates in the larger masses. Foliation is generally concordant with that of the gneisses, an exception being the mass east of Tête-à-la-Baleine which is partly discordant. Screens of gneissic material and inclusions are common particularly around the contacts.

The granite is pale red and composed essentially of large potash felspar phenocrysts (fig.16, p.45) in a medium- to coarse-grained matrix of essentially quartz and potash felspar with plagioclase, biotite, hornblende, and opaque minerals. The range in mineral composition is given in Table IV, No.3 (p.26). Foliation is poor and results from the preferred orientation of the felspar phenocrysts.

Granodiorite is light grey to light brownish grey and medium- to coarse-grained, composed essentially of plagioclase and quartz, with potash felspar, biotite, hornblende, and opaque minerals. The range in mineral composition is given in Table IV, No.4 (p.26). Large phenocrysts of light grey plagioclase and large augen-like crystals of potash felspar are common (fig.17, p.45), but are not as abundant as the potash felspar phenocrysts in the granite. Foliation is well-developed due to the segregation of mafics and quartz felspar aggregates, and the parallel orientation of phenocrysts and augen.

Mineralogy

The mineralogy is essentially the same as that of the gneisses. Plagioclase composition covers approximately the same range An_{25-34}, but the average for granitic and granodioritic varieties is $An_{29.1}$ and $An_{30.6}$ respectively. Alteration of the oligoclase to albite and sericite in the granitic varieties is similarly a common feature. Hornblende has the same pleochroic formula in green and brown but the extinction angle tends to be a little higher. $z \wedge C = 13\text{-}33^{\circ}$ (average 18.8°) and $2V_x = 54\text{-}78^{\circ}$ in 8 thin sections.

Mode of emplacement

The granitic plutons are deep-seated intrusives corresponding to those of the catazone of Buddington's (1959) classification. They intruded during or before folding and were affected by the last metamorphic event. Concordance with the gneisses suggests that they may be part of a large sill-like body but no base of such a body was seen and they are better described as domes. The 'mantled' domes of Eskola (1948) might very well apply as the granite appears to be related to a particular stratigraphic level.

LATE METAMORPHOSED IGNEOUS ROCKS

Included in the late group of metamorphosed igneous rocks are basic, intermediate, and acid rocks that have not been strongly deformed mechanically, but have been affected at least partly by chemical alteration ascribed to a late stage of the Grenville 'event'. Age relations within the group are not well established but aplite granite cuts intermediate rocks and pegmatite cuts gabbro.

Gabbro

Three bodies of relatively unaltered olivine and hornblende gabbro were mapped. Contacts of two of the gabbros, one in Lac La Sarre and the other 1/2 mile west of Étang Belon, were not seen but the Lac La Sarre occurrence appears to be a neck-like body no more than a 1/4 mile in diameter. The third and best exposed occurrence is in Lac du Chevreuil and is approximately 700 feet wide and 3/4 to possibly 1½ miles long and is intrusive into flat-lying gneisses. The Lac du Chevreuil mass consists of a resistant core of olivine gabbro surrounded by a zone of easily weathered hornblende gabbro. Olivine gabbro also forms a resistant mass in Lac La Sarre. In Lac du Chevreuil a 3-foot width of hornblende gabbro is exposed at one point at the contact with the gneisses and is altered to hornblende-biotite-andesine gneiss with a strong foliation parallel to the contact. Except at the contact the rock is medium-grained and ophitic and the plagioclase is strongly zoned. Layering parallel to the contact and steeply dipping is evident in places and probably results from magmatic flow. Olivine gabbro is associated with and grades into hornblende gabbro which is the more common variety. Both varieties are hard, medium-grained, and olive black.

Microscopic features

The olivine and hornblende gabbros are mineralogically similar and the typical olivine gabbro consists of plagioclase, hypersthene, clinopyroxene, olivine, and hornblende, with accessory amounts of biotite, opaques, spinel, and apatite. Chlorite, serpentine, sericite, and carbonate, and some black opaques are alteration minerals. The mineralogical compositions of two olivine gabbros and two hornblende gabbros are given in Table VI, Nos.1-4.

Plagioclase laths are well twinned and strongly zoned with cores up to 15 percent more calcic than the rims. The most calcic grain observed was labradorite (An_{70}) and fine incipient alteration

Table VI

Estimated mineralogical composition - Gabbro

	1	2	3	4
	Vol.%	Vol.%	Vol.%	Vol.%
Plagioclase	35-40	63	60	50
	An_{70}(max.)	An_{65}(max.)	An_{55}	
Potash felspar	-	-	Tr.	-
Olivine	10	5	-	-
Pyroxene				
ortho-	5	28		10
clino-	20		9	20
Hornblende	30	3	26	20
Biotite	-	1	2	-
Chlorite	Tr.	-	Tr.	-
Opaques	Tr.	-	2	-
Apatite	-	Tr.	1	-
Serpentine	-	Tr.	-	-
Spinel	Tr.	-	-	-
Carbonate	Tr.	-	-	-
		100	100	

1. Olivine gabbro - Lac du Chevreuil
2. Olivine gabbro - Lac La Sarre
3. Hornblende gabbro - Lac La Sarre
4. Hornblende gabbro - Lac du Chevreuil

Nos. 1 and 4 are visual estimates each on a single thin section. Nos. 2 and 3 are modal analyses on single thin section counting 500-1000 points.

of calcic cores is evident.

Olivine occurs as rounded to irregular grains almost invariably surrounded by pyroxene and slightly altered to serpentine and magnetite along cracks. The texture is ophitic to diabasic depending on whether the orthopyroxene or clinopyroxene dominates. Clinopyroxene is colourless and clouded due to incipient alteration and occurs as large skeletal crystals enclosing plagioclase laths. Orthopyroxene is a clear pleochroic pale red to colourless hypersthene occurring as small stubby anhedral to subhedral grains surrounding olivine and in some cases alters to hornblende (fig.18). It appears either earlier or later than the clinopyroxene (fig.19). Hornblende is anhedral and is strongly pleochroic in browns and biotite with similar pleochroism is in some cases closely associated with it.

Accessory minerals include black opaques, green spinel, and subhedral to anhedral grains of apatite. Carbonate, chlorite, sericite, serpentine, and some opaques are alteration minerals. In some cases almost the entire rock is altered to chlorite, and remnants of the original dark minerals are very pale coloured, with a faded appearance.

Age

The relatively weak alteration of the rock with the preservation of olivine, zoned plagioclase, and the original texture sets these rocks apart from the older meta-gabbros. The altered contact zone of the Lac du Chevreuil body is sharp against the country rock and is relatively narrow. The gabbros appear to be volcanic necks which intruded towards the close of the period of metamorphism.

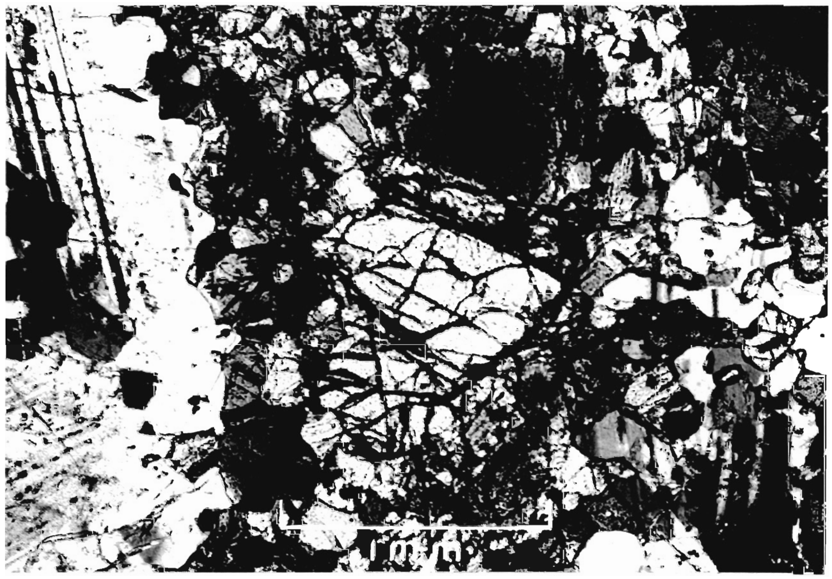


Fig. 18 - Gabbro showing olivine (light grey centre) surrounded by small crystals of hypersthene (grey), and both surrounded by small crystals of amphibole (dark grey). Labradorite is twinned and zoned (light grey to white). Crossed nicols. X 35.

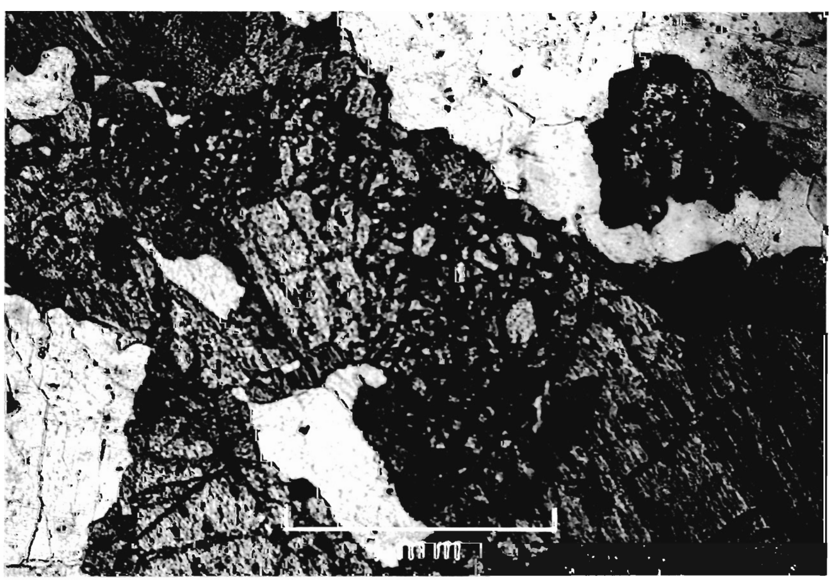


Fig. 19 - Small crystals of hypersthene (grey) in a large crystal of clino-pyroxene (grey), and both surrounded by small crystals of amphibole (dark grey). Plagioclase is white. Plain light. X 35.

Intermediate Intrusives

Intruded at the close of the Grenville metamorphic period were a number of rocks of intermediate composition. They are not strongly deformed mechanically but have undergone many of the chemical changes that affected the gneisses. They include small discordant intrusive stocks near Île Lecouvre and on Île Paul Nadeau (east of St.Augustin area), as well as dykes and sills in the eastern half of the area.

Île Lecouvre intrusive

The Île Lecouvre intrusive includes a number of small islands south of Île Lecouvre. Little of the intrusion is exposed and visits to the islands were cut short by bad weather. Contacts with the gneisses and coarse-grained foliated porphyritic granite may be exposed immediately south of Île Lecouvre but were not observed. However, on the most northern of the Îles Fox group paragneisses and coarse-grained porphyritic granodiorite are cut by two dykes of coarse-grained green monzonite, one foot and two feet wide respectively. The intrusion also transects the foliation of the rocks to the north on Île Lecouvre.

Green quartz monzonite : The quartz monzonite is dusky yellow green to light olive grey, medium- to coarse-grained, and remarkably homogeneous. The colour is distinctive, but unlike the green pyroxene-plagioclase gneisses the rock is massive and only occasionally is a faint foliation discernible. Dykes of aplite and diabase, and both dykes and irregular masses of pegmatite cut the quartz monzonite.

Microscopic features : Mineralogically the green quartz monzonite is similar to the granodiorite-quartz monzonite dykes (p.58) and consists essentially of plagioclase (approximately An_{30}), microcline perthite, quartz, hornblende, biotite, and opaque minerals (including pyrite). Accessory minerals include apatite, sphene, and zircon. Chlorite, carbonate, and muscovite occur as alteration minerals. The texture is allotriomorphic. The estimated composition is given in Table VII, No.1.

Plagioclase is slightly altered to sericite and twin lamellae are often bent and/or fractured, with thin films of chlorite along many of the fractures. Many grains are antiperthitic and myrmekite is common adjacent to potash felspar. The potash felspar is weakly twinned perthitic microcline. Quartz exhibits strong undulatory extinction and contains oriented rutile needles.

Hornblende, the dominant mafic constituent, is strongly pleochroic from pale brown to green. It is subhedral, and alters to chlorite. Biotite is pleochroic from pale brown to dark reddish brown. Flakes are sometimes bent and large skeletal-like flakes suggest a late, possibly deuteric, formation. Alteration to chlorite, carbonate, and muscovite is common.

Zircon is present as rounded grains and prisms. Subhedral crystals of apatite are common, and sphene occurs as irregular grains often associated with the opaque minerals.

Granite : The granite is coarse-grained, massive, and pale red with a spotted appearance on the outcrop. It is identical with some of the rock types on Île Paul Nadeau (Warren, 1964). It is cut by diabase and contains many angular to rounded inclusions of quartz, meta-gabbro, calc-silicate rocks, and grey paragneisses.

Microscopic features : The granite consists essentially of

Table VII

Estimated mineralogical composition - Intermediate intrusives

	1	2	3	4	5	6
	Vol.%	Vol.%	Vol.%	Vol.%	Vol.%	Vol.%
Quartz	25	20	14	8	10	4
Plagioclase	38	20	39	50	31	36
			An_{23-24}	An_{25-27}	An_{25-27} + albite	An_{26-28}
Potash felspar (perthite)	20	50	26	7	36	35
Hornblende	7	7	5	16	4	17
Biotite	2	2	5	7	7	2
Chlorite	Tr.	Tr.	2	-	4	-
Opaques	3	Tr.	6	8	5	4
Zircon	Tr.	-	Tr.	Tr.	Tr.	Tr.
Carbonate	Tr.	-	1	-	1	Tr.
Apatite	Tr.	Tr.	2	4	2	2
Sphene	Tr.	Tr.	-	Tr.	Tr.	-
Sericite	Tr.	-	-	-	-	-
			100	100	100	100

1. Green quartz monzonite - Île Lecouvre
2. Granite - Île Lecouvre
3. Quartz monzonite dyke
4. Granodiorite dyke
5. Quartz monzonite dyke
6. Monzonite dyke

Nos. 1-2 are visual estimates each on a single thin section.

Nos. 3-6 are modal analyses on a single thin section counting 500-100 points.

oligoclase, twinned perthitic microcline, strained quartz, biotite, and hornblende, with traces of apatite, opaques, sphene, and chlorite. The estimated composition is given in Table VII, No.2 (p.57). Plagioclase shows slight zoning with partial alteration to albite and sericite. It formed earlier than the microcline which generally surrounds and appears to replace it.

Other occurrences : Small occurrences of rocks similar to those on Île Lecouvre were observed on Île Galibois south of Île Longue and west of St.Augustin river in the northwest corner of the St.Augustin sheet. A good exposure on Île Paul Nadeau outside the area, about 1½ miles east of Île Galibois, was studied by Warren (1964). All these rocks clearly cut and contain subangular to rounded inclusions of the gneisses, calc-silicate rocks, and amphibolites. The rocks on Île Paul Nadeau are definitely cut by aplites and are closely associated with granodiorite-quartz monzonite-monzonite dykes and sills.

Dykes and sills of granodiorite-quartz monzonite-monzonite

A group of dykes and sills of quartz-monzonite, monzonite, and granodiorite composition are abundantly exposed on the coast near St.Augustin. They occur less frequently westwards and are almost completely absent west of Baie des Ha! Ha!

The rock is generally medium- to fine-grained and in some cases contains plagioclase phenocrysts or large flakes of biotite. Contacts tend to be a little finer grained but this is not a striking feature. The rock is brownish grey to greyish olive and occasionally pale red, and when rich in pink felspar the dark weathered surface has a pale pink or pale red-purple tint.

The dykes are 1 to 150 feet wide, have sharp contacts, and foliation where observed is parallel to the contacts and best developed in biotite-rich varieties. Some dykes have quartz-felspathic veins or segregations parallel to the foliation (fig.20), and in a few cases these veins are drag folded (fig.21). Jointing is well-developed and makes the dykes more easily weathered than the country rock. Some joints are confined to the dykes but others continue into the gneisses and are younger. Early minor faults show strong dragging in the dykes (fig.22).

The dykes and sills are cut by pegmatite and aplite veins, and in one case by a diabase dyke. Inclusions of amphibolite and calc-silicate rock were seen in several of these dykes and one dyke was observed cutting an amphibolite.

Microscopic features : All the dykes are composed essentially of plagioclase, potash felspar, and quartz. These make up about 2/3 to 3/4 of the rock, with hornblende, biotite, and opaques constituting the rest. Disseminated pyrite and apatite are common and minor amounts of zircon are always present. Alteration minerals are chlorite, carbonate, sphene, and sericite. Modal analyses of 4 typical specimens are given in Table VII, Nos.3-6 (p.57). Mafic minerals show varying degrees of preferred orientation while the felsic minerals occur as a granular mosaic.

Finely twinned oligoclase (An_{23-28}) is generally slightly altered to sericite, and in a few cases it has been partially altered to albite and sericite in the same way as it is in the gneisses. Antiperthite replacement of the plagioclase by potash

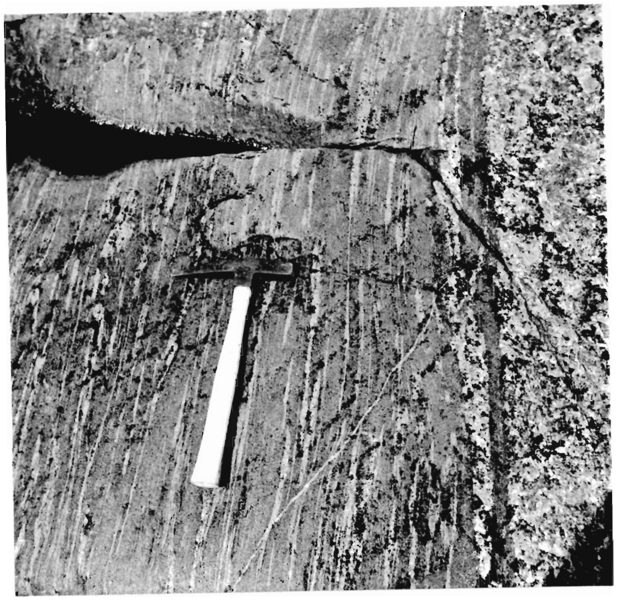


Fig. 20 - Intermediate grano diorite dyke cutting coarse-grained pink porphyritic granite. Quartz-felspar veins or segregations are parallel to the contacts.

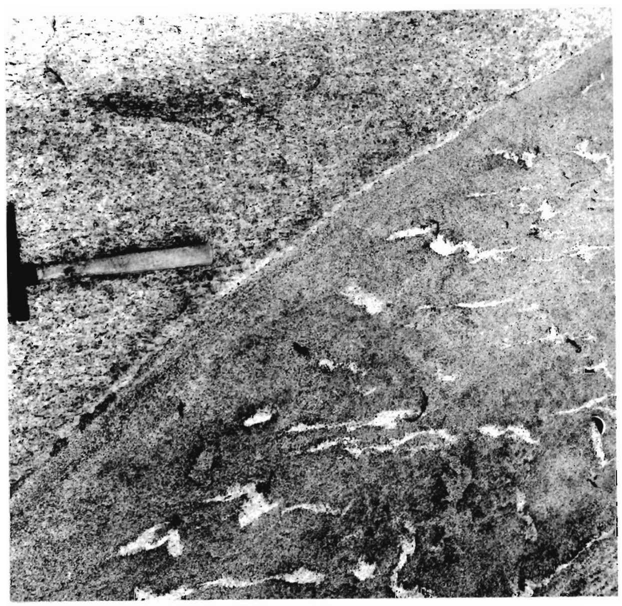


Fig. 21 - Drag folding of quartz-felspar veins or segregations in an intermediate granodiorite dyke.

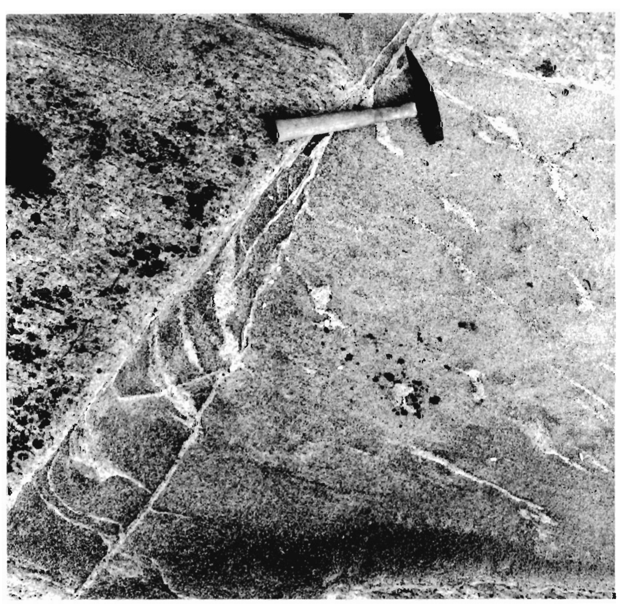


Fig. 22 - Intermediate grano diorite dyke cut by a fault with a 2-foot horizontal right hand displacement. The quartz-felspar veins or segregations have been dragged on the fault plane.

felspar was observed in some cases. Potash felspar is always perthitic, and when present in minor quantities is interstitial together with quartz to the plagioclase.

Anhedral to subhedral hornblende is strongly pleochroic in light browns and dark greens and may be partially or completely altered to chlorite, and in most cases appears to have undergone late magmatic or deuteric alteration to biotite. Biotite occurs also as large irregular poikilitic flakes, pleochroic from light to dark brown. Black opaque minerals occur in fairly large discrete grains, while leucoxene is disseminated through the chlorite.

Subhedral to euhedral apatite is relatively abundant and small rounded subhedral prisms of zircon are common. Sphene occurs as rims around magnetite and more commonly as irregular grains. Carbonate occurs with the mafic minerals as an alteration product.

Age of intermediate intrusives

The granodiorite-quartz monzonite-monzonite dykes and the Île Lecouvre intrusion are apparently related. They are older than the diabase dykes but younger than the gneisses, the porphyritic granite, and at least some of the amphibolites. Of importance is the fact that albitization of the plagioclase occurs in these rocks as well as in the gneisses and that there is strong alteration of the mafic constituents. The dykes intruded joint planes, are unaffected by regional folding, have their own joint system which is cut by later joints, and their foliation is parallel to their contacts and is clearly the result of flow during intrusion. The above features suggest a time of intrusion after consolidation of the gneisses but while minor mechanical adjustments were still taking place and conditions were suitable for chemical adjustments both to the gneisses and the intrusives.

Acidic Aplites and Pegmatites

Aplites and pegmatites are related to both the early and late metamorphosed igneous rocks. Many are exposed but the total volume is small.

Early pegmatites are irregular coarse-grained varieties of the rock in which they occur, and late pegmatites are rare straight-walled dykes 8 inches to 6 feet wide, generally composed of quartz, felspar, biotite, and hornblende, and in many cases magnetite, and in rare cases garnet. A late 15-25 feet wide pegmatite on Île Wakeham contains a little fluorite and pyrite. Many irregular pegmatites cannot be placed in either the early or late groups.

Aplites belong to both groups and many are not easily assigned to either group. Some of the fine-grained pink granitic gneisses may be aplite sills. Many aplites clearly belong to the late group as they cut the intermediate intrusives, and some are straight-walled like the intermediate dykes. Three of the latter were accompanied by small lateral displacements along strike.

Quartz Veins

Quartz veins are rare but important and two occurrences in meta-gabbro are associated with sulphides. An occurrence on the north shore of Baie Querry consists of lenses 1-1½ inches wide and 1-2 feet long parallel to the foliation. In Anse de l'Argile a 2-4 feet wide zoned quartz vein is exposed over 65 feet. The quartz is rich in pyrite, and over a length of 25 feet has a core up to 2 feet wide of coarse-grained massive pyrrhotite containing a little pyrite and rare molybdenite, and cut by veins of chalcopyrite. These quartz veins are lense-shaped with irregular widths due to folding or replacement in contrast to the quartz veins of the younger dyke system which fill straight-walled fractures.

MUTTON BAY ALKALI SYENITE PLUTON

INTRODUCTION

The Mutton Bay pluton is a circular body which is centred on Tabatière and has a diameter of about 15 miles. The western half is well-exposed, and forms a resistant mass rising well above the surrounding gneisses (fig.23) to reach a maximum elevation of 884 feet. Much of the eastern half of the pluton is submerged beneath the sea. However, a number of well-situated islands help clarify the over-all geological picture.

The pluton was first mentioned, and briefly described by Longley (1944a). Kranck visited Mutton Bay in 1948 and suggests (Kranck, 1961) that the syenite may be the same age as those associated with anorthosites, indicating that there may be undiscovered anorthosites in the region. Anorthosites were discovered by Hale (1962) 36 miles northwest of the syenite pluton. Hale states that the syenite is an unknown quantity in terms of economic mineral potential. On the recent "Tectonic Map of the Canadian Shield" (G.S.C. Map 4-1965) the syenite is outlined for the first time on a large-scale composite map. It is included in the Grenville orogeny and its discordant nature is not mentioned. An accurate outline of the pluton, with some structural data and a general description, has been published in a preliminary report by the author (Davies, 1965b).

The sea covers half the pluton and the coastline provides an excellent and near complete cross-section of it, extending from Mutton Bay in the south to Anse Bastien in the north. Most of the

Fig. 23 - View from Île Fecteau west to Anse Bastien showing the abrupt change in elevation between the relatively weak peneplained gneisses (right) and the resistant rugged syenite (left). Arrow shows the syenite-gneiss contact.

Fig. 24 - North Pioneer at Mutton Bay in early June 1962. Note the abundant outcrop with low scrub (dark) in the valleys and hollows. Buildings in the foreground are built on coarse-grained massive pink quartz syenite, and the hills behind are coarse-grained foliated pink syenite. View looking north from south side of bay.

data gathered comes from this and other wave-washed sea shores. Away from the seashore the moss cover on rocks, discontinuous exposure, rapid decomposition of the coarse-grained rocks, and the rounded nature of the outcrops do not allow one to study the finer details, but exposure is abundant and contacts can be fairly accurately defined. Fig.24 (p.65) shows the abundant outcrop found in the western half of the pluton.

GENERAL GEOLOGY

The Mutton Bay syenite pluton with its satellitic dykes is the youngest Precambrian intrusive in the area. It cuts the gneisses and porphyritic granite, shows no sign of having been metamorphosed, but exhibits abundant features found only in magmas.

It is a 'multiple injection' layered body. At least 23 distinct mappable units are recognized which occur as roughly concentric rings and arcs. They are divided, according to age, into three major groups - early, intermediate, and late - with each group having its own distinct characteristics. A fourth group occurs but is of minor importance. Age relations are given in Table VIII. The attitude of flow foliation in the various units and the exposed unit contacts are steep near the walls of the pluton but generally dip inwards at decreasing angles on approaching the core. Most rocks of the pluton are syenites, quartz syenites, or pyroxene syenites. There are minor amounts of granite as well as mafic-rich hybrids formed by differentiation during and after intrusion of the normal varieties. Rocks are fine- to very coarse-grained, massive, to extreme trachytoidal, and often porphyritic, with a pink, grey, or green colour.

Table VIII

Table of Formations for the Mutton Bay Intrusion

<table>
<tr><td>Fourth Group</td><td colspan="3">Pinkish grey pegmatitic syenite
Medium-grained syenite with pegmatitic phase</td></tr>
<tr><td colspan="4">Intrusive Contact</td></tr>
<tr><td rowspan="5">Late Group</td><td colspan="3">Coarse-grained greyish orange pink very well foliated syenite</td></tr>
<tr><td colspan="3">General Intrusive Relation</td></tr>
<tr><td colspan="3">Coarse-grained dark greenish grey very well foliated syenite</td></tr>
<tr><td colspan="3">Intrusive Contact</td></tr>
<tr><td colspan="3">Coarse-grained light grey very well foliated syenite</td></tr>
<tr><td colspan="4">Intrusive Contact</td></tr>
<tr><td rowspan="11">Intermediate Group</td><td rowspan="6">Grey Felspar Subgroup</td><td colspan="2">Medium-grained very well foliated grey syenite</td></tr>
<tr><td colspan="2">Intrusive Contact</td></tr>
<tr><td colspan="2">Medium- to coarse-grained well foliated grey syenite</td></tr>
<tr><td colspan="2">Intrusive Contact</td></tr>
<tr><td colspan="2">Medium-grained grey syenite porphyry</td></tr>
<tr><td colspan="2">Intrusive Contact</td></tr>
<tr><td colspan="3">Porphyritic olive grey syenite and light coloured differentiates</td></tr>
<tr><td colspan="3">Intrusive Contact</td></tr>
<tr><td colspan="3">Medium- and medium- to coarse-grained greenish to pinkish grey granite</td></tr>
<tr><td colspan="3">Intrusive Contact</td></tr>
<tr><td colspan="3">Fine-grained syenites and porphyritic syenites</td></tr>
<tr><td colspan="4">Intrusive Contact</td></tr>
<tr><td rowspan="9">Early Group</td><td rowspan="3">Foliated Sphene-bearing group</td><td>Pale red porphyritic quartz syenite</td><td rowspan="5">Coarse-grained massive pink quartz syenite to syenite (Younger phase at Mutton Bay)</td></tr>
<tr><td>Intrusive Contact</td></tr>
<tr><td>Light brownish grey well foliated syenite</td></tr>
<tr><td colspan="2">- ? - ? - ? - ? - ? - ? - ? -</td></tr>
<tr><td colspan="2">Medium- to coarse-grained green pyroxene quartz syenite</td></tr>
<tr><td colspan="3">Intrusive Contact</td></tr>
<tr><td colspan="3">Coarse-grained foliated pink syenite
- ? - ? - ? - ? - ? - ? -
Coarse-grained massive pink quartz syenite to syenite (older phase at Mutton Bay)
Pink quartz syenite and granite (contact phase)</td></tr>
<tr><td colspan="3">Intrusive Contact</td></tr>
<tr><td colspan="3">Coarse-grained green pyroxene quartz syenite
Coarse-grained green pyroxene syenite</td></tr>
</table>

Satellitic dykes include basic lamprophyres, aplites, and pegmatites, followed by acidic and pyroxene-hydronepheline veins.

PETROLOGY OF THE PLUTONIC ROCKS

Early Group

The oldest members of the early group are green or pink, coarse-grained, and generally massive, though a pink syenite at Mutton Bay is an exception and is well foliated. At the contacts with the gneisses the oldest syenites of the group are quartz-rich and this is believed the result of contamination. The youngest members of the group are medium- to coarse-grained, foliated, and in most cases porphyritic. Apart from the initial intrusion of coarse-grained green pyroxene syenite, all intrusions are in the form of thick steeply-dipping cone sheets.

A. Coarse-grained green pyroxene syenite

Green pyroxene syenite forms the centre of the pluton and is best exposed around Tabatière. The dominant rock is coarse-grained, massive with hypidiomorphic texture, but a weak flow foliation, conspicuous on the weathered surface, is developed in some places. The rock is greyish olive green on the fresh surface and weathers first to a dark yellowish brown and finally to very light grey. Felspars are green like the rock and occur as irregular grains or subhedral laths ($\frac{1}{2}$ x 1 cm. in cross-section) which sometimes show simple twinning and are not as platy as in the younger intrusives. Black ferromagnesian minerals occur as single grains or clusters averaging $\frac{1}{2}$ cm. in diameter.

Microscopic features : Rock-forming minerals include microperthite (patches of cryptoperthite), oligoclase, augite, hornblende, biotite, olivine, and magnetite. Apatite is an accessory. White mica, serpentine, chlorite, and carbonate are secondary minerals. Modal analysis and optical properties of minerals are given in Table IX, No.1.

Euhedral apatite and subhedral magnetite crystallized early and occur as inclusions in all other mafic minerals. Olivine, when not altered to serpentine, is subhedral and yellowish grey. Augite is subhedral to anhedral and is rimmed by, or intimately intergrown with anhedral hornblende, generally strongly coloured in orange and green. The green of the hornblende sometimes has a bluish tint and some grains have uncoloured patches. Ragged flakes of biotite rim the earlier mafic minerals.

Microperthite occurs as irregular anhedra and laths, almost always showing broad simple twinning and encloses about 5 percent early-formed irregular grains of twinned oligoclase (An_{18}). Mafic constituents generally lie interstitial to the felspars but small biotite flakes occur in the oligoclase and are absent, or are small and appear corroded in the perthite. This suggests that the oligoclase crystals are not in equilibrium with their surroundings and may be xenocrysts.

Light olive to dark yellowish brown serpentine is pseudomorphous after pyroxene, and with associated magnetite is pseudomorphous after olivine. Chlorite and white mica and carbonate are found in the felspars.

A medium-grained variety of this unit at Tabatière contains

Table IX

Modal Analyses and Optical Properties - Early Group

	1	2	3	4	5	6	7	8
Microperthite	79.7	88.7	90.7	88.6	92.7	88.4	95.4	87.2
Quartz	-	0.6	-	0.6	-	2.9	-	3.8
Olivine	6.0	-	-	-	-	0.3	-	-
Pyroxene	0.3	5.3	4.0	Tr.	1.3	0.6	-	-
Amphibole	6.7	2.5	Tr.	Tr.	1.0	4.4	2.4	3.5
Biotite	4.6	0.2	2.1	3.1	1.7	Tr.	0.8	3.0
Apatite	0.2	Tr.	0.2	Tr.	Tr.	0.1	0.2	Tr.
Black Opaques	1.2	2.3	2.2	2.1	1.3	2.0	0.9	0.7
Sphene	-	-	Tr.	-	-	-	0.3	1.1
Zircon	-	Tr.	-	Tr.	Tr.	Tr.	-	-
Sulphides	-	-	-	0.1	-	0.2	Tr.	-
Carbonate	Tr.	-	-	0.6	1.0	0.1	-	-
Chlorite	0.3	}0.4	0.8	4.9	1.0	1.0	Tr.	0.7
Serpentine	1.0		-	-	-	Tr.	-	-
<u>Pyroxene</u>								
2Vz	63°	63°	62°		63°	71°		
$x \wedge C$	43°	40°	45°		39°	38°		
X	v.p.gn	v.p.gn			cl-gnh			
Y	v.p.gn	cl						
Z	v.p.b	v.p.b						
<u>Amphibole</u>								
2Vx	58°	55°	84°		74°	74°	79°	47°
$z \wedge C$	15°	13°	24°		23°	17°	16°	30°
X	gyh.o	ds.y	v.p.o		p.gn.y	v.p.o	gyh.o	p.ol
Y	l.ol	gyh.o	p.y.b		l.ol.b	gyh.y.gn	p.gn	d.y.b
Z	m.y.gn	p.ol	p.ol			p.ol	l.b	m.ol.b
<u>Plagioclase</u>								
%An	12	12	11	11	10	7	7	4
<u>Potash felspar</u>								
2Vx	63°	64°	49°,69°	50°	56°	47°	50°	59°
<u>Biotite</u>								
Ny	1.680	1.688	1.658	1.657	1.642	1.664	1.662	1.662
<u>Olivine</u>								
2Vx	-	-	-	-	-	-	-	-

<u>Symbols for pleochroic colours</u> : v - very ; p - pale ; gn - green ; cl - colourless ; gnh - greenish ; b - brown ; ds - dusky ; y - yellow ; gyh - greyish ; o - orange ; ol - olive ; l - light ; m - moderate

<u>Samples</u>

1. Coarse-grained green pyroxene syenite (A-30)
2. Coarse-grained green pyroxene quartz syenite (T-31-6)
3. Coarse-grained massive pink quartz syenite to syenite (T-16-44) Older phase at Mutton Bay
4. Coarse-grained massive pink quartz syenite to syenite (T-16-39) Younger phase at Mutton Bay
5. Coarse-grained foliated pink syenite (T-16-31)
6. Medium- to coarse-grained green pyroxene quartz syenite (T-21-8)
7. Light brownish grey well foliated syenite (T-22-26)
8. Pale red porphyritic quartz syenite (T-22-35)

conspicuous amounts of calcite and large flakes of biotite ½-1 cm. in diameter.

B. Coarse-grained green pyroxene quartz syenite

The green pyroxene quartz syenite is found in contact with the gneisses between Anse Bastien and Lac du Gros-Mécatina, and on Murr and Buffitt Islands near the presumed southeast contact. It is coarse-grained with hypidiomorphic texture, and displays a weak flow foliation which is best developed at the contact with the gneisses in varieties low in quartz. The colour of the rock is imparted by the felspar and on the fresh surface is a dusky yellow green and on the weathered surface a light olive grey. Subhedral felspar laths (1 x ½ to 2 x ½ cm. in cross-section) invariably show simple twinning. Mafic minerals are black and occur interstitial to the felspar as clusters and single crystals (2-4 mm. in diameter). Quartz in places lies interstitial to the felspar and its presence is believed the result of contamination.

Microscopic features : The rock-forming minerals are microperthite (often with cryptoperthite cores), augite, hornblende, and magnetite, with minor amounts of biotite, quartz, apatite, and zircon. Secondary minerals are chlorite and serpentine. See Table IX, No.2 (p.70) for modal analysis and optical properties of minerals.

Euhedral to subhedral apatite was first to crystallize, followed by anhedral to subhedral magnetite. Both are found as inclusions in the other mafic minerals. A single subhedral zircon (0.6 mm. in diameter) was observed lying interstitial to the felspar. Subhedral augite crystallized at about the same time as the magnetite and, together with the magnetite, is altered to a light olive serpentine and a colourless chlorite. Hornblende is entirely anhedral, occurring as individual grains and rims around pyroxene. Some grains are zoned, their rims having a bluish tint and being deeper green than the centres. Ragged flakes of biotite rim the hornblende. The coloured and opaque minerals are generally interstitial to, but are occasionally enclosed by the felspar.

Felspar occurs as subhedral laths and irregular anhedra, generally greater than 3 mm. in diameter, but at the Anse Bastien contact fine anhedra (0.1 mm. in diameter) together with mafic minerals occur interstitial to, and in fractures cutting the large felspar crystals. Quartz which is interstitial to the felspar is relatively free of strain, suggesting that it crystallized after the fracturing of the felspar. The potash felspar component of the perthite has $2V_x = 64^\circ$ (Anse Bastien) and $2V_x = 78^\circ$ (Murr Island). These are the highest $2V_x$ values for potash felspar obtained in rocks of the early group. In the contact aureole $2V_x = 47\text{-}52^\circ$ which corresponds to that of the youngest early syenites, and is probably a reflection of the structural state and composition of the felspar in the gneisses .

C. <u>Coarse-grained massive pink quartz syenite to syenite</u>

The coarse-grained massive pink syenites underlie a large part of the pluton and form the outer zone of the early group of intrusives. Intrusion was at least in part after that of the coarse-grained green pyroxene quartz syenite found at the contacts. There was more than one injection of material as is the case at Mutton Bay where a lense-like mass about 1/2 mile wide cuts an older massive pink quartz syenite to the south and a foliated pink syenite to the north. The younger massive variety has felspar laths that are more platy and have a redder colour than the older variety. On islands around Île Fecteau two varieties occur. These differ essentially in colour, and the one occurs as xenoliths in the other. The relation of the coarse-grained massive pink syenites to the coarse-grained massive green pyroxene syenite of the core of the pluton is not clear, but the medium- to coarse-grained green pyroxene quartz syenite clearly cuts the coarse-grained massive pink quartz syenite. A red alteration of green syenites occurs locally along fractures and joints and confuses the picture. Near the contact at Anse Bastien coarse-grained green pyroxene quartz syenite occurs as patches in the coarse-grained massive pink quartz syenite and also forms a halo around some xenoliths of gneiss in the latter, indicating that the green quartz syenite is the older. In the field quartz was more conspicuous in this unit near the borders of the pluton.

The rock is coarse-grained and equigranular with an allotriomorphic texture. The colour is essentially a pale red which is paler on the weathered surface. Felspar crystals 1 x 3 cm. in cross-section are common but average $1\frac{1}{2}$ x $1\frac{1}{2}$ cm., and most crystals show simple twinning. Larger crystals have medium grey cores and pale red borders, while those interstitial to the large crystals are pale red. The core of some large crystals exhibits a blue iridescence and these crystals are most conspicuous in the younger red variety at Mutton Bay. Mafic constituents are evenly distributed with black biotite conspicuous, occurring in books 1/2 - 1 cm. in diameter. Quartz occurs interstitial to the felspar and in miarolitic cavities. Chalcopyrite is a visible but minor accessory.

Microscopic features : Rock-forming minerals are microperthite (with patches of cryptoperthite), quartz, biotite, hornblende, augite, and magnetite. Apatite, zircon, sphene, and chalcopyrite are accessory minerals. Carbonate and chlorite are alteration minerals. Modal analyses and optical properties of minerals are given in Table IX, Nos.3 and 4 (p.70).

Subhedral to euhedral apatite crystallized early and is enclosed in subhedral magnetite. Sphene is closely associated with the magnetite and occurs as irregular grains or clusters of grains. Augite is anhedral towards magnetite but is otherwise subhedral and is rimmed by anhedral hornblende. The latter is not particularly abundant. The most widespread mafic mineral is biotite, forming partial or complete reaction rims around magnetite.

Quartz, sometimes accompanied by carbonate and chlorite, is commonly present and lies interstitial to anhedra or irregular laths of felspar. It occasionally shows well-developed faces and is only weakly strained.

Felspar is slightly altered to chlorite and carbonate, while augite is generally strongly altered to a colourless to pale green chlorite. Alteration products pseudomorphous after olivine are not found.

D. Coarse-grained foliated pink syenite

Between Île Mécatina and Mutton Bay the syenite is a fairly well foliated red variety which becomes more massive in places. Unlike the foliated red syenite of the late group it is resistant to weathering, probably because of its low mafic content and less perfect foliation, and it is relatively free of inclusions.

The rock is coarse-grained, consisting of irregular felspar laths, with conspicuous twinning and an average dimension in cross-section of 0.5 x 1.0 cm. Except for the cores of felspar crystals which are medium grey, the colour of the remaining felspar and the rock as a whole is moderate reddish orange and is preserved on the weathered surface. Mafic minerals lie interstitial to the felspar as irregular grains or clusters about 0.5 cm. in diameter, and their removal by weathering gives the surface a pitted appearance.

Microscopic features : Rock-forming minerals are microperthite (patches of cryptoperthite), hornblende, biotite, magnetite, and augite. Accessory minerals are apatite and zircon. Chlorite and carbonate are alteration products. Modal analysis and optical properties of minerals are given in Table IX, No.5 (p.70).

Subhedral to euhedral apatite crystallized early followed by subhedral to anhedral magnetite. Subhedral augite which has altered readily to chlorite and carbonate crystallized next and is rimmed by anhedral hornblende. Biotite occurs as ragged flakes forming partial to complete reaction rims around magnetite. The mafic minerals lie interstitial to subhedral and anhedral laths of felspar.

E. Medium- to coarse-grained pink syenite to granite

Medium- to coarse-grained pink syenite to granite occurs at a number of points around the contact of the pluton and probably resulted partly from melting and assimilation of the adjacent gneisses. It is generally medium-grained but coarse-grained varieties occur southwest of Mutton Bay. In many cases it intrudes the country rock. It is similar to the pink syenites except for the high quartz and low mafic content and can be seen grading into normal pink syenite southwest of Mutton Bay.

F. Medium- to coarse-grained green pyroxene quartz syenite

Medium- to coarse-grained green pyroxene quartz syenite is well exposed on Île Fecteau and at Baie-de-la-Terre, where it is 2/5 of a mile wide and cuts the coarse-grained massive pink syenites. The rock has a hypidiomorphic texture and consists of subhedral felspar laths 5-10 mm. long and 3-5 mm. wide showing simple twinning. A weak flow foliation is particularly evident near the contacts. Colour of the felspar and also the rock is light olive grey but the cores of the felspar crystals are darker than the rims and many show a blue iridescence. Mafic minerals occur as grains up to 3 mm. in diameter.

This unit is very similar to the green pyroxene quartz syenite of the contact but differs macroscopically in colour, grain size, and the common occurrence in this unit of sulphides. Dark grey cognate xenoliths are common near the contacts.

Microscopic features : The rock-forming minerals are microperthite (cores of cryptoperthite), quartz, aegyrine-bearing augite, hornblende, olivine, and magnetite. Accessory minerals are apatite, biotite, pyrite, chalcopyrite, and zircon. Alteration minerals are chlorite, carbonate, and serpentine. Modal analysis and optical properties of minerals are given in Table IX, No.6 (p.70).

Subhedral apatite and subhedral magnetite crystallized early, the magnetite often enclosing the apatite. Zircons are euhedral to subhedral, scarce, and about 0.1 mm. in diameter. Euhedral aegyrine-bearing augite crystals, displaying a 'schiller' structure, are generally rimmed by anhedral hornblende. The latter is darker coloured at the rims with green pleochroic colours having a bluish tint. Olivine is subhedral, enclosing apatite, and is older than the magnetite. Biotite is rare, generally occurring as small flakes around magnetite. Pyroxene alters to pale green chlorite, carbonate, and light olive serpentine, but some serpentine is probably after olivine.

Felspar occurs as irregular anhedra or subhedral laths displaying a zoning both in the type of perthite and the distribution of numerous small mafic inclusions in their cores. The inclusions are pyroxene, amphibole, and magnetite, often accompanied by small biotite flakes. The presence of biotite is accompanied by greater un-mixing of the perthite. The formation of biotite, involving both the magnetite inclusions and the potash felspar, possibly catalysed the un-mixing. Occasional corroded cores of felspar crystals are free of inclusions but contain much chlorite along cracks and fractures. The potash felspar component of the perthite has a $2V_x = 47^\circ$, the lowest value for potash felspar found in rocks of the pluton. Clear quartz, only slightly strained, lies interstitial to the felspar.

G. Foliated sphene-bearing sub-group south of Mutton Bay

Close to the contact with the gneisses, and best developed south of Mutton

Bay, are a group of foliated syenites which intrude the coarse-grained massive pink variety. The age relations within the group are given in Table X below. There are essentially two types, a well foliated one and a porphyritic one.

<table>
<tr><th colspan="2">Table X</th></tr>
<tr><td rowspan="3">Porphyritic phases</td><td>Medium- to coarse-grained well foliated slightly porphyritic pale red syenite with rounded cognate xenoliths of medium-grained dark grey porphyritic syenite</td></tr>
<tr><td>Intrusive Contact</td></tr>
<tr><td>Medium-grained 'pale red' syenite (porphyritic near contacts, with fine-grained grey cognate xenoliths)</td></tr>
<tr><td></td><td>Intrusive Contact</td></tr>
<tr><td rowspan="3">Well foliated phases</td><td>Very coarse-grained pegmatite
Medium- to coarse-grained very well foliated light brownish grey syenite</td></tr>
<tr><td>Intrusive Contact</td></tr>
<tr><td>Medium- to fine-grained very well foliated light brownish grey syenite</td></tr>
</table>

Light brownish grey well foliated syenite : The well foliated type includes medium- to fine-grained, medium- to coarse-grained, and very coarse-grained pegmatite phases. Fine varieties occur as xenoliths in the coarse varieties. The rock is light brownish grey with a well-developed flow foliation. Felspar crystals have medium grey cores and moderate orange pink rims and occur as subhedral laths exhibiting simple twinning. Mafic minerals are black but not conspicuous.

Microscopic features (medium- to coarse-grained phase) : Rock-forming minerals are microperthite (patches of cryptoperthite), hornblende, magnetite, and biotite. Apatite, sphene, and chalcopyrite are accessory minerals. Chlorite is an alteration mineral. Modal analysis and optical properties of minerals are given in Table IX, No.7 (p.70).

Subhedral to euhedral apatite crystallized early followed by subhedral magnetite. Sphene is unusually abundant and occurs as irregular grains closely associated with, and as partial rims around the magnetite. Pyroxene which would normally take up the titanium in the melt is not present. Hornblende is anhedral, showing incipient alteration to chlorite, while biotite completely or partially rims the magnetite. Mafic minerals generally lie interstitial to the felspar.

<u>Pale red porphyritic quartz syenite</u> : The porphyritic type includes two phases, both pale red and very similar. It is characterized by the presence of numerous rounded medium dark grey cognate xenoliths and of subhedral felspar phenocrysts, 5-10 mm. in diameter, which lie in a matrix of felspar grains, 1-3 mm. in diameter. The cores of the felspar phenocrysts are similar to the dark felspar in the xenoliths and are rimmed by pale red felspar like that which also constitutes the matrix. Xenoliths were broken up in the magma and fractures perpendicular to the foliation of the xenoliths are common. Flow foliation is strongly developed at the intrusive contacts.

Microscopic features : Rock-forming minerals are microperthite (Patches of cryptoperthite), quartz, amphibole, biotite, magnetite, and sphene. Apatite is an accessory mineral and chlorite an alteration mineral. Modal analysis and optical properties of minerals are given in Table IX, No.8 (p.70).

Subhedral to euhedral apatite is enclosed in anhedral to subhedral magnetite (0.5 mm. in diameter) and anhedral to subhedral sphene (0.25 mm. in diameter). The latter rims the magnetite. Amphibole (1 mm. in diameter) is subhedral and shows incipient alteration to chlorite. Ragged flakes of biotite are associated with the magnetite.

Felspar exhibits simple twinning and the cores of large crystals, which contain numerous small mafic inclusions and are also less un-mixed than the rims, are believed to be derived from the breaking up of cognate xenoliths.

Intermediate Group

Following the early group is a complex of smaller intrusives which occupy a zone between the coarse-grained massive green pyroxene syenite of the centre and the coarse-grained red quartz syenite of the border of the pluton. The best exposures are at Lac Salé (north side of the bay), Tabatière (from the wharf to the north, approximately 1 mile), and from Pointe Rouge south to Île Mécatina. The latter section is composed almost entirely of these rocks.

The group is inhomogeneous and includes fine- and coarse-grained rocks, either green or grey, rarely red. Almost all the rocks exhibit a flow foliation and the most conspicuous feature of the group is the abundance of porphyritic varieties.

A Fine-grained syenites and porphyritic syenites

Fine-grained syenites and porphyritic syenites intruded the massive syenites of the early group as a swarm of narrow cone sheets. There were repeated intrusions, each cutting those before, and containing xenoliths of them. Later intrusions into the same zone blur the already complex picture. The rocks are very similar, differing slightly in colour and texture. The best exposures are those north of the Tabatière wharf and at Pointe Rouge. At both places a division into three main phases, an early porphyritic syenite, a non-porphyritic syenite, and a late syenite porphyry, holds good.

Fine grain size is characteristic and most of the rocks are to some extent porphyritic. Flow foliation is invariably present and in some cases a faint layering is seen. Mafic minerals occur in the layered varieties as thin films or layers that generally exhibit a lineation down-dip. These rocks also exhibit pinch and swell structures which formed during intrusion of the late group.

The earliest intrusive phases are porphyritic with phenocrysts of either grey, olive grey, or pale brown felspar, one or other characteristic of a phase. Felspar phenocrysts are generally less than 5 mm. long which is smaller than those of the later porphyries, and in three common varieties constitute about 10 per-cent of the rock. Mafic minerals occur as disseminated black clusters, 1-2 mm. in diameter, or as streaks and layers 1-3 mm. to rarely 20 mm. thick. Many phases are most often found as xenoliths, and it is probable that many of the phenocrysts of these rocks are in fact xenocrysts derived from assimilation of the country rock.

Intruding the early porphyritic phases is a fine-grained dark greenish grey foliated pyroxene syenite. Specimens are more typically a light olive grey due to alteration extending at least 6 inches below the surface. Occasional small felspar phenocrysts may be present but are not conspicuous and the rock is essentially non-porphyritic. At Pointe Rouge the green variety grades into a pale red variety.

Cutting the non-porphyritic phase are the very distinctive syenite porphyries, with felspar phenocrysts constituting about 25 percent of the rock. There are at least three separate phases. Phenocrysts are much larger (10-15 mm. in diameter) and more abundant than in the earlier porphyritic syenites. Colour of the matrix may be either medium dark grey, pale yellowish brown, or greyish olive, and the phenocrysts are light brown or light olive grey. At Tabatière a pale yellowish brown variety with light brown phenocrysts grades into a fine-grained, non-porphyritic, pale yellowish brown syenite which appears to be related to the fine-grained light olive grey pyroxene syenite. It is possible that the felspar phenocrysts are xenocrysts and represent the undigested part of partially assimilated country rock. Xenoliths of coarse-grained massive pink syenite occur in these rocks. The felspar of the xenoliths is identical in colour and grain size to the phenocrysts in all except the green porphyries where the phenocrysts are the same colour as the matrix.

On Île Verte are a number of green syenites, some of which belong to this group. Among fine-grained and porphyritic syenites like those described above is a medium- to coarse-grained well foliated grey-green syenite similar to the green syenites of the late group.

Microscopic features of fine-grained porphyritic syenite : Rock-forming minerals are cryptoperthite (minor microperthite), amphibole, biotite, and magnetite. Apatite, sphene, and zircon are accessory minerals. Carbonate and chlorite are alteration products. Modal analysis and optical properties of minerals are given in Table XI, No.1.

Subhedral to euhedral magnetite and apatite crystallized early. Anhedral sphene occurs alone and as rims around magnetite. Subhedral to anhedral amphibole grains, 0.1 mm. in diameter, and clusters, 0.5-1.0 mm. in diameter, enclose both magnetite and sphene. Anhedral to subhedral biotite surrounds amphibole and magnetite and is interstitial to or enclosed in the borders of felspar crystals.

Chlorite and carbonate occur as a fine alteration of perthite.

Microscopic features of fine-grained light olive grey foliated pyroxene syenite : Rock-forming minerals are microperthite, augite, amphibole, and magnetite. Apatite is an accessory mineral. Serpentine is an alteration after pyroxene and perhaps olivine. Modal analysis and optical properties of minerals are given in Table XI, No.2.

Subhedral to euhedral magnetite is the most abundant mafic constituent. Subhedral apatite is enclosed in the felspar, whereas apatite interstitial to the felspar is anhedral and coarser-

Table XI

Modal Analyses and Optical Properties - Intermediate Group

	1	2	3	4	5	6	7	8
Perthite	79.8	91.1	85.1	82.0	89.6	83.2	85.8	89.1
Quartz	-	-	-	12.7	0.2	2.6	0.6	-
Olivine	-	-	1.0	-	-	-	-	-
Pyroxene	-	2.3	4.0	1.1	1.6	-	2.6	0.4
Amphibole	11.8	1.8	2.7	3.1	5.2	11.8	9.9	8.7
Biotite	2.1	-	5.5	-	0.7	0.4	Tr.	-
Apatite	1.5	0.8	Tr.	Tr.	0.3	0.3	Tr.	Tr.
Black Opaques	3.1	3.4	1.4	0.8	1.4	0.7	1.1	0.5
Sphene	0.5	-	Tr.	-	-	-	-	-
Zircon	0.1	-	-	Tr.	0.2	0.2	-	-
Carbonate	0.4	-	0.1	-	-	-	-	-
Chlorite	0.7	-	-	-	0.8	0.4	-	-
Serpentine	-	0.6	0.2	0.3	Tr.	0.4	Tr.	1.3
Allanite	-	-	Tr.	-	-	-	Tr.	-
Pyroxene								
2Vz		59°	70°	80°	57°		67°	
$x \wedge C$		48°	38°		41°		33°	
X		m.gn.y	d.yh.gn				p.ol	
Y		p.y.gn	me.y.gn				p.gn	
Z		l.ol.b	y.gy				p.ol	
Amphibole								
2Vx	53°	59°	23°	25°	65°	22°	18°	25°
$z \wedge C$				32°	18°			
X	me.y.b	gyh.o	m.y.b	d.y.b	gy.y	gyh.o	gyh.o	gyh.o
Y	d.y.b	me.ol.b	d.y.b	d.y.gn	l.ol.gy	ds.y	m.ol.b	ds.y.gn
Z	gyh.ol	ds.y.gn	ds.y.gn	ol.gy	p.ol	ds.y.gn	m.b	
Plagioclase								
% An	-	-	13	5	0	4	7	0
Potash felspar								
2Vx	-	-	55°	-	50°	-	68°	68°
Biotite								
Ny	-	-	1.693	-	-	-	-	-
Olivine								
2Vx	-	-	-	-	-	-	-	-

Symbols for pleochroic colours : m - moderate ; gn - green ; y - yellow ; d - dark ; yh - yellowish ; p - pale ; ol - olive ; me - medium ; l - light ; b - brown ; gy - grey ; o - orange ; gyh - greyish ; ds - dusky

Samples

1. Fine-grained porphyritic syenite (A-8-5)
2. Fine-grained light olive grey foliated pyroxene syenite (A-8-6)
3. Medium- to coarse-grained well foliated grey green syenite (T-15-2)
4. Medium to coarse-grained greenish to pinkish grey granite (T-21-3)
5. Porphyritic olive grey syenite (T-6-16)
6. Medium-grained grey syenite porphyry (T-15-32)
7. Medium- to coarse-grained well foliated grey syenite (T-15-16)
8. Medium-grained very well foliated grey syenite (T-15-19)

grained. Subhedral to euhedral augite crystallized early and alters to light olive brown serpentine, some of which is probably after olivine. Anhedral amphibole surrounds the augite and the magnetite.

Felspar anhedra, 0.1-0.3 mm. long, exhibit a good flow foliation and occasional anhedra 2.0 mm. long give the rock a weak porphyritic texture. Minute mafic inclusions occur in the core of felspar crystals, but the cores are not corroded.

Microscopic features of medium- to coarse-grained well foliated grey green syenite : Rock-forming minerals are microperthite (patches of cryptoperthite), aegyrine-bearing augite, olivine, amphibole, biotite, and magnetite. Accessory minerals include apatite, sphene, and allanite. Carbonate, chlorite, and serpentine are alteration minerals. Modal analysis and optical properties of minerals are given in Table XI, No.3 (p.84).

Subhedral prisms of apatite crystallized early with subhedral to anhedral magnetite and in one case magnetite encloses a pyroxene crystal. Pyroxene is subhedral and generally lies interstitial to the felspar, but some small crystals are enclosed in the felspar. The pyroxene crystals are zoned and have a darker rim with a higher $2V_z$ than the core. Pale yellowish grey olivine is subhedral and crystallized at about the same time as the pyroxene. A moderate reddish brown subhedral allanite crystal is enclosed in amphibole and is surrounded by a weak pleochroic halo. Brown to green anhedral amphibole surrounds pyroxene and olivine and, where associated with olivine, has a bluish tint. A little colourless to blue riebeckite is also present. Anhedral biotite surrounds magnetite and to a lesser degree the other mafic minerals. It is pleochroic in browns but flakes surrounding riebeckite are pleochroic in green and brown. Mafic minerals are generally interstitial to the felspar but small crystals of pyroxene, amphibole, and biotite occur in the felspar as inclusions. Chlorite occurs as thin films in the felspar and moderate yellow to light olive serpentine is an alteration after olivine.

B. <u>Medium- and medium- to coarse-grained greenish to pinkish grey granite</u>

Granite is of limited occurrence and is mappable at Lac Salé and exposed as xenoliths on Île Mécatina. There are essentially two varieties, a medium-grained greenish grey, and a medium- to coarse-grained pinkish grey variety, both of which are pale yellowish brown on the weathered surface. In places the two appear to grade into one another, but elsewhere the coarser intrudes the finer variety.

The texture is hypidiomorphic. Felspar crystals, up to 1 cm. in diameter and the same colour as the rock, exhibit simple twinning. Quartz occurs interstitial to the felspar, and green to black mafic minerals are evenly distributed, occurring in clusters 2-4 mm. in diameter, which in the medium-grained variety give rise to a faint lineation.

Microscopic features : Rock-forming minerals are microperthite, quartz, amphibole, aegyrine-augite, and magnetite. Apatite, zircon, and sphene are accessory minerals. Serpentine is an alteration mineral. Modal analysis and optical properties of minerals are given in Table XI, No.4 (p.84).

Subhedral to euhedral apatite is relatively rare and is enclosed in mafic minerals and felspar. Zircon is subhedral to euhedral. Sphene occurs in some specimens and is rare. Anhedral magnetite is enclosed in amphibole but lies interstitial to the felspar, suggesting that the felspar crystallized before the mafic minerals. Aegyrine-augite is strongly coloured, is anhedral, lies interstitial to the felspar, and alters to a moderate yellow serpentine. Some pseudomorphs after pyroxene are anhedral. Amphibole is anhedral, lies interstitial to the felspar, and occurs as rims around pyroxene and magnetite.

Felspar is anhedral and roughly equidimensional, but in the medium-grained variety it tends to occur as laths which are euhedral towards quartz and amphibole. The perthite is strongly un-mixed. Quartz is only weakly strained and crystallized with carbonate interstitial to the felspar.

C. <u>Porphyritic olive grey syenite</u>

Porphyritic olive grey syenite is the oldest widely exposed member of the intermediate group. Exposures on the seashore at Île Mécatina and at Lac Salé are small, but away from the shore to the west it is up to 1 mile wide and is resistant to erosion, forming some of the highest points of the Mutton Bay intrusion.

The small exposure at Lac Salé is important and very complex in detail (fig.25). The most important feature is the gradation from a coarse-grained pale yellowish brown variety, through a coarse-grained yellowish grey, into the typical porphyritic olive

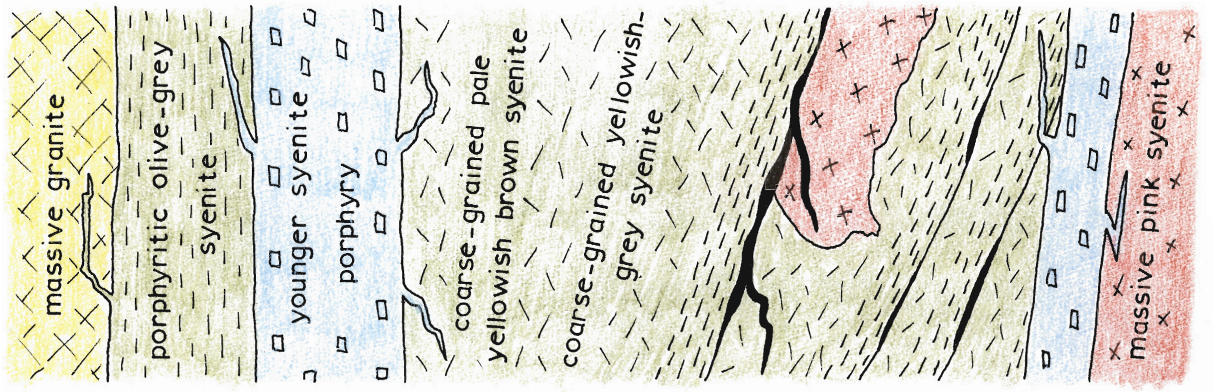


Fig. 25 - Simplified skematic section across the exposure of porphyritic olive grey syenite. Seal Point, Lac Salé.

grey syenite both at the upper and lower contacts. The lower part of the sequence is repeated, indicating repeated intruding pulses of magma. Variation appears in part due to gravity differentiation as mafic segregations (1-4 inches thick) occur at the bottom of each repeated sequence. The lower contacts of each sequence are sharp and the foot-wall is injected by the mafic segregations and the porphyritic olive grey syenite. The hanging-wall of the last differentiated sequence is a homogeneous porphyritic olive grey syenite, and is a roof concentration of small felspar crystals or a chilled contact but with no mafic concentration. The same differentiated sequence is found in a block on the south side of the bay near Lac Salé village.

The light-coloured varieties of the sequence in fig.25 are massive and very similar in appearance to the massive rocks of the early group. It is possible that the light varieties in some cases may have been overlooked on traverses inland. Dark cognate xenoliths found in contact zones of other intrusive phases of the pluton may represent contact differentiates like those above, that were broken up by later pulses of magma.

Normal porphyritic olive grey syenite : The most characteristic feature of this rock is its dark olive grey colour which, in exceptionally fresh specimens, is a medium bluish grey. It is porphyritic, consisting of felspar laths 5-10 mm. long and 1-2 mm. thick in a fine-grained matrix, and exhibits a fairly well-developed flow foliation. Mafic minerals occur as minute crystals or disseminated clusters up to 1 mm. in diameter.

Microscopic features : Rock-forming minerals are microperthite (cryptoperthite in cores of phenocrysts), amphibole, augite, magnetite, biotite, and quartz. Accessory minerals are apatite, sphene, and zircon. Serpentine and chlorite are alteration minerals. Modal analysis and optical properties of minerals are given in Table XI, No.5 (p.84).

Euhedral apatite and subhedral to anhedral magnetite, in some cases enclosed in felspar, crystallized early. Euhedral to subhedral zircon crystals are older than the magnetite and are relatively abundant, while sphene is associated with the magnetite and is enclosed by a brown amphibole. Pyroxene crystallized early as subhedral to anhedral grains and some euhedral crystals are enclosed in felspar. Two amphiboles occur, a dominant early brown variety and a younger variety pleochroic in blues and greys. The brown variety occurs as anhedral grains up to 2 mm. in diameter and as rims around pyroxene, and large grains enclose small felspar crystals. The younger amphibole surrounds the pyroxene and the brown amphibole. Ragged biotite flakes are relatively rare, crystallizing after the amphiboles. Pyroxenes and amphiboles alter to a colourless to pale green chlorite, and a moderate yellow serpentine, associated with chlorite and magnetite, may be after olivine.

Felspar occurs as anhedral to subhedral phenocrysts in a groundmass of anhedral felspar. The large felspar crystals have cryptoperthite cores free of inclusions, surrounded by borders with abundant inclusions and strongly exsolved perthite. The inclusions appear to have catalysed the unmixing of the perthite. Fractures in the felspar are filled with chlorite. Quartz is rare and lies interstitial to the felspar.

Light-coloured differentiates of the porphyritic olive grey syenite : The light-coloured differentiates are coarser grained than the normal dark variety, with felspar crystals 8-10 x 3 mm. in cross-section, but they differ very little mineralogically. A typical specimen contains approximately 90 percent perthite, 6 percent pyroxene, and 2 percent biotite, with lesser amounts of magnetite, apatite, and chlorite.

The pyroxene is pleochroic in greens, encloses magnetite and apatite, and is rimmed by biotite. Chlorite with magnetite may be pseudomorphous after olivine. Some felspar grains have concentrations of inclusions in their cores.

D. <u>Grey felspar sub-group</u>

These rocks are the youngest and least complex of the intermediate group. They are exposed from Baie Rouge south to Île Mécatina, on the west side of Île du Gros-Mécatina, and on some smaller islands. Similar-looking rocks occur elsewhere as minor intrusions.

There are essentially three types, an early medium-grained grey syenite porphyry, followed by a medium- to coarse-grained well foliated grey syenite, and finally a medium-grained very well foliated grey syenite. The three types are closely related. They are essentially grey to green in colour and all contain zoned felspar crystals visible in hand specimen.

<u>Medium-grained grey syenite porphyry</u> : The rock, which occurs as rounded outcrops, is medium-grained, porphyritic, and light brownish grey, and is either massive or exhibits a weak flow foliation. The matrix is composed of pale red subhedral felspar crystals, $\frac{1}{2}$ x 2 to 1$\frac{1}{2}$ x 5 mm. in cross-section, and black mafic minerals occur interstitial to the felspar in clusters 1-6 mm. in diameter. Biotite is conspicuously absent in hand specimen. Zoned felspar phenocrysts account for about 20-25 percent of the rock and are medium dark grey with lighter grey rims and cores. The dark intermediate zone contains minute mafic inclusions. Phenocrysts range in size from a little larger than the matrix felspar to 5 x 2$\frac{1}{2}$ cm. in cross-section, and some exhibit simple twinning.

Microscopic features : Rock-forming minerals are microperthite, quartz, amphibole, magnetite, and biotite. Apatite, zircon, and sphene are accessory minerals. Chlorite and serpentine are alteration minerals. Modal analysis and optical properties of minerals are given in Table XI, No.6 (p.84).

Subhedral to euhedral apatite crystallized early with subhedral magnetite, and both are enclosed in felspar and amphibole. The amphibole, which also encloses sphene, is invariably anhedral, is strongly coloured, often with blue borders and blue zones surrounding magnetite inclusions, and lies interstitial to the felspar. It alters to a moderate yellow to light olive serpentine. Ragged flakes of biotite crystallized after the amphibole. Mafic minerals generally occur interstitial to the felspar but also as small inclusions in the felspar, particularly as concentrations in the cores of phenocrysts. Un-mixing of the felspar is generally well developed but in the phenocrysts is variable with a zonal arrangement in part rhythmic. The cores of the felspar crystals are least un-mixed. The potash component of the perthite exhibits microcline twinning which is unusual in the pluton. Quartz is relatively free of strain and lies interstitial to the felspar.

<u>Medium- to coarse-grained well foliated grey syenite</u> : The unit cuts the medium-grained grey syenite porphyry and is intimately associated with the medium-grained very well foliated variety which intrudes and assimilates it. It is very much like members of the late group, being coarse-grained with an excellent trachytoidal texture, but differs in colour and mineralogy, and contains scattered felspar phenocrysts. The colour of both the felspar and the rock is pale olive. Felspar occurs as thin subhedral plates 2-3 mm. thick and 5-20 mm. long, and many are zoned with dark cores and light rims. Mafic minerals occurring as individual grains or groups of

grains 1-7 mm. in diameter are black, anhedral, and interstitial to the felspar. Biotite is conspicuously absent in the hand specimens.

Microscopic features : Rock-forming minerals are microperthite, amphibole, aegyrine-augite, magnetite, biotite, and quartz. Apatite and allanite are accessory minerals. Serpentine and chlorite are alteration minerals. Modal analysis and optical properties of minerals are given in Table XI, No.7 (p.84).

Euhedral apatite is enclosed in early subhedral magnetite. Pyroxene is subhedral with some grains showing simple twinning and it alters to chlorite and a moderate yellow serpentine. Anhedral amphibole surrounds pyroxene and lies interstitial to the felspar. It is strongly coloured with a blue tint near magnetite inclusions and borders of grains. Biotite is rare and surrounds some of the magnetite. The felspar contains occasional small mafic inclusions, while unstrained quartz lies interstitial to it. Allanite is anhedral and encloses apatite. It is greyish orange and zoned and has patches strongly pleochroic from light to moderate brown.

Medium-grained very well foliated grey syenite : This is the youngest member of the sub-group and is well exposed with the other members from Pointe Rouge south to Île Mécatina, and on the west side of Île du Gros-Mécatina. Its well-developed jointing gives rise to pronounced cliffs and a rugged shoreline. It is porphyritic, light olive grey, and displays an excellent flow foliation resulting from the alignment of thin subhedral felspar plates. Felspar phenocrysts 1-2 x 3-10 mm. in cross-section usually have dark cores and light borders, but the inner part of the core of some grains is also light-coloured. Many phenocrysts are undoubtedly xenocrysts derived from the assimilation of the intruded rocks (fig.74, p.176). Simple twinning in the felspar is common. Mafic constituents occur as disseminated grains less than 1 mm. in diameter, but in rare cases form clusters that give rise to a weak lineation (figs.76 and 77, p.182). A characteristic of this unit is a dusky red haematite-staining occurring as patches in the rock about 1 cm. in diameter and penetrating the walls of joints or fractures up to 6 inches. The same staining occurs in the very similar rocks of the fourth group.

Microscopic features : Rock-forming minerals are microperthite (some cryptoperthite cores), amphibole, magnetite, and aegyrine-augite. Accessory minerals are apatite, carbonate, and sphene. Alteration minerals are chlorite, carbonate, biotite, and serpentine. Modal analysis and optical properties of minerals are given in Table XI, No.8 (p.84).

Apatite crystallized early with, and is in some cases enclosed in subhedral to anhedral magnetite. Subhedral sphene is rare. Pyroxene occurs in minor amounts and is strongly altered to moderate yellow serpentine. Amphibole is anhedral and surrounds pyroxene or its alteration products.

Felspar is subhedral to anhedral. Phenocrysts have a corroded core containing a few mafic inclusions surrounded by a border containing numerous minute mafic inclusions which increase in size towards the border. Carbonate occurs interstitial to the felspar and in narrow veins. Haematite is apparently responsible for the red staining and occurs as irregular grains with carbonate and chlorite along grain boundaries, fractures, and cleavages in felspar.

Late Group

Thick cone sheets of rocks belonging to the late group occur at Lac Salé and narrow cone sheets cut rocks of the intermediate group in a zone surrounding the core of coarse-grained massive green pyroxene syenite at Tabatière. The cone sheets dip in general towards the centre of the pluton and are parallel or sub-parallel to the foliation of the host rock.

Rocks of the late group are some of the most striking of the intrusion. They are coarse-grained, composed of euhedral to sub-hedral platy felspar crystals, 2-3 cm. long, 1-2 cm. wide, and 1-3 mm. thick, showing a pronounced preferred orientation or trachytoidal texture. Simple twinning of the felspar is con-spicuous and many felspar plates are bent and fractured. Mafics occur interstitial to the felspar and include subhedral to euhedral magnetite, pyroxene, and olivine, and anhedral biotite and amphi-bole. The colour of the rock in all except mafic concentrations is that of the felspar and is generally greyish orange pink or dark greenish grey, and in some cases light grey, but gradations between these colours are found.

Differentiation by gravity settling and in some cases by magma flow is much in evidence. Flow features are common and in-clude scouring and orientation of platy crystals with development of mineral lineation.

The group may be divided into three units on the basis of colour as colour differences reflect differences in mineralogy. Green varieties are fayalite-pyroxene syenites, grey varieties are pyroxene syenites, and pink varieties are amphibole-biotite syenites. Gradations between the three units result from differentiation within single intrusions. Segregated material, differing in colour and mineralogy from the main intrusion is generally of minor importance, and the intrusion as a whole can be readily assigned to one of the three units. Mafic concentrations are of two kinds, those containing pyroxenes and olivines, in which case the accompanying felspar is green, and those composed essentially of amphiboles, where the accompanying felspar is pink.

At Lac Salé all three units are found as distinct intrusions. The oldest is a medium- to coarse-grained very well foliated light grey syenite. This is cut by coarse-grained very well foliated dark greenish grey mafic-rich syenite which in turn is cut by coarse-grained, very well foliated greyish orange pink syenite. Each unit is composed of more than one intrusive phase or magma pulse, and each phase exhibits differentiation. The three main units probably result from differentiation at depth.

Some rocks of the group are similar to the coarse-grained foliated pink syenite between Mutton Bay and Île Mécatina, which belongs to the early group, but members of the late group are richer in mafics, better foliated, and show greater variation in colour than the latter.

<u>Microscopic features of coarse-grained light grey very well foliated syenite</u> : Rock-forming minerals are microperthite (patches

of cryptoperthite), aegyrine-augite, amphibole, and biotite. Accessory minerals are apatite, magnetite, sphene, zircon, and carbonate. Chlorite is an alteration mineral. Modal analyses and optical properties of minerals are given in Table XII, Nos. 1 and 2.

Euhedral apatite, subhedral to anhedral magnetite and associated anhedral sphene crystallized early. Some apatite is enclosed in magnetite, and sphene generally crystallized around magnetite and apatite. Aegyrine-augite crystals, many containing small inclusions of carbonate, are generally subhedral. Some euhedral to subhedral pyroxene crystals are enclosed in anhedral amphibole. The amphiboles are strongly coloured in olive and brown, but some crystals are rimmed by a blue variety. Anhedral biotite crystallized after the amphibole. Mafics are generally interstitial to the felspar but they occur with carbonate as inclusions in the microperthite. Un-mixing of the perthite is more intense in the mafic-rich varieties of the rock. Carbonate is widely disseminated and occurs interstitial to the felspar as well as inclusions in the other minerals.

<u>Microscopic features of coarse-grained dark greenish grey very well foliated syenite</u> : Rock-forming minerals are cryptoperthite (to microperthite), fayalite, aegyrine-bearing augite, amphibole, biotite, and magnetite. Accessory minerals are allanite, apatite, and zircon. Serpentine and magnetite are alteration minerals. Modal analyses and optical properties of minerals are given in Table XII, Nos.3 and 4.

Early crystallizing anhedral to subhedral magnetite encloses

Table XII

Modal Analyses and Optical Properties - Late Group

	1	2	3	4	5	6
Perthite	92.0	55.5	66.0	89.6	90.9	27.3
Quartz	-	-	-	-	-	-
Olivine	-	-	4.0	-	-	0.8
Pyroxene	0.9	22.3	10.1	-	-	25.2
Amphibole	3.7	3.8	8.8	4.1	6.9	29.9
Biotite	2.1	14.6	4.0	1.5	1.5	
Apatite	0.1	0.5	0.2	0.5	0.3	Tr.
Black Opaques	0.9	0.2	6.9	1.4	0.4	16.8
Sphene	0.1	0.1	-	0.1	Tr.	-
Zircon	-	-	-	-	Tr.	-
Carbonate	0.2	3.0	-	0.2	-	-
Serpentine	-	-	Tr.	2.6	-	-
Pyroxene						
2Vz	87°		68°			
x∧C	18°		39°			
X	m.gn		l.gn			
Y	m.gn		p.gn			
Z	p.ol		gyh.y.gn			
Amphibole						
2Vx	42°		55°		38°	
z∧C	17°		15°		13°	
X	p.y.b		v.p.o		p.y.b	
Y	m.b		gyh.b		gyh.b	
Z	gyh.ol		l.ol.b		gyh.ol	
Plagioclase						
% An	4	0	10	12	12	
Potash felspar						
2Vx	-	62°	-	-	74°	
Biotite						
Ny	1.703	1.709	1.700	-	1.696	
Olivine						
2Vx	-	-	51°	-	-	

Symbols for pleochroic colours : m - moderate ; gn - green ; l - light ; p - pale ; ol - olive ; gyh - greyish ; y - yellow ; b - brown ; v - very ; o - orange

Samples

1. Coarse-grained light grey very well foliated syenite (T-11-3)
2. Coarse-grained light grey very well foliated syenite - mafic-rich variety (T-11-6)
3. Coarse-grained dark greenish grey very well foliated syenite - moderately mafic-rich (T-14-1)
4. Coarse-grained dark greenish grey very well foliated syenite (RD-52-4)
5. Coarse-grained greyish orange pink very well foliated syenite (T-14-6)
6. Mafic concentration in coarse-grained greyish orange pink very well foliated syenite (T-13-4)

euhedral apatite. Subhedral to anhedral yellowish grey fayalite is partially altered to moderate yellow serpentine and magnetite. Subhedral to anhedral pyroxene crystallized around the olivine, and both pyroxene and olivine are partly surrounded by strongly coloured anhedral amphibole. Finally, ragged biotite flakes form rims around the early mafic minerals. The felspar is relatively free of inclusions. It is cryptoperthitic with microperthitic crystal borders. Carbonate is generally interstitial. Light brown allanite and zircons in biotite are surrounded by pleochroic halos.

Microscopic features of coarse-grained greyish orange pink very well foliated syenite : Rock-forming minerals are microperthite (patches of cryptoperthite), amphibole, biotite, augite, and magnetite. Accessory minerals are sphene, apatite, and carbonate. Alteration minerals are carbonate and chlorite. Modal analysis and optical properties of minerals are given in Table XII, No.5 (p.98). Modal analysis of a mafic concentration is given in Table XII, No.6 (p.98).

Subhedral to anhedral magnetite is partially rimmed by anhedral sphene and crystallized early with euhedral apatite. Pyroxene is rare. Strongly coloured amphibole is generally anhedral but sometimes subhedral. The generally brown to olive grains are in many cases bluish around the edges. Some grains are pleochroic from colourless to light blue green. Anhedral biotite encloses the other minerals. Bending of some biotite flakes suggests that movement was not complete when the biotite crystallized. Carbonate is an alteration mineral and also occurs interstitial to the felspar closely associated with the biotite.

Carbonate and chlorite fill fractures in the felspar. Alteration of amphibole to chlorite, carbonate, and felspar or quartz is seen in some sections.

Fourth Group

The fourth group includes rocks of minor areal extent that intruded at a late stage and are characterized by the presence of a pegmatite phase.

A. Medium-grained syenite with pegmatite phase

This is a minor unit exposed near Tabatière. It is important in that it is similar in many respects to the medium-grained very well foliated grey syenite of the intermediate group, but differs in that it is accompanied by a very coarse-grained pegmatitic phase. It cuts members of the late group at Pointe Rouge and contains inclusions of fine-grained and porphyritic syenites of the intermediate group at Point au Grace. The colour of the rock is essentially a pale olive and, as in its counterpart of the intermediate group, very dark red haematite staining is common.

Microscopic features : The rock consists of microperthite (88.6%), aegyrine-bearing augite (3.4%), amphibole (5.2%), magnetite (1.6%), biotite (0.1%), chlorite (1.1%), and apatite (Tr.).

Apatite occurs as euhedral crystals which crystallized early followed by subhedral magnetite. Pyroxene crystallized next as subhedral to anhedral grains, some of which are slightly altered to chlorite. It is yellowish green with moderate pleochroism and has $2V_z = 70^\circ$ and $z \wedge C = 47^\circ$. Amphibole invariably rims the pyroxenes and lies interstitial to the felspar. It has $2V_x = 27^\circ$, X = greyish orange, Y = dark yellowish brown, and Z = moderate olive brown. Simple twinned anhedral felspar plates have a strong preferred orientation.

B. Pinkish grey pegmatite syenite

Pegmatite syenite cuts medium- to coarse-grained green quartz syenite of the early group on Île Fecteau. As no rocks were observed cutting it, its position cannot be established with certainty. Its amphiboles are like those of the intermediate or fourth group and, being pegmatitic, suggests a relation to the latter.

The rock is essentially a massive pale yellowish brown coarse-grained to very coarse-grained pegmatite, consisting of felspar crystals up to 3 cm. in diameter. In places the large felspar crystals have a medium- to coarse-grained matrix. Black mafic minerals are either biotite, occurring in books 2 cm. in diameter and ½ cm. thick, or amphibole, occurring as anhedral crystals 1-2 cm. in diameter.

Microscopic features : A thin section of the amphibole variety consists of microperthite (83%), and amphibole (15%), with minor amounts of quartz (1%), and magnetite (1%), and traces of biotite, apatite, zircon, sphene, and a yellow alteration mineral with carbonate.

Apatite and zircon occur as euhedral to subhedral prisms and crystallized early. Magnetite was generally late, lying interstitial to the amphibole, but some was early, and together with sphene is enclosed in the amphibole. Amphibole is subhedral to anhedral and is strongly pleochroic in green and brown with a bluish tint in some cases. The perthite is anhedral to subhedral with quartz interstitial to it. A yellow alteration mineral and carbonate are probably after pyroxene.

GEOCHEMISTRY OF THE PLUTONIC ROCKS

Nine rocks were selected as being representative of the Mutton Bay intrusive suite, and each was analysed for 20 major and minor oxides and elements by the Department of Natural Resources Laboratories, Quebec. The analyses are tabulated together with the Niggli norms in Table XIII.

Variation of major oxides with respect to SiO_2

Fig. 26 is a Harker variation diagram for the major oxides plotted against SiO_2, and shows an increase of Al_2O_3, Na_2O, and K_2O, and a decrease of CaO, FeO, Fe_2O_3, TiO_2, MgO , P_2O_5, H_2O, and MnO with increasing SiO_2 content. In some cases there is a sharp change of trend at the SiO_2-rich end, due to the presence of considerable free quartz in the sample richest in silica, which is a granite and quantitatively of minor importance. The relatively good correlation of points for each element shows that the rocks could have crystallized from a continuous series of related magmatic liquids.

The nine analyses represent three major intrusive groups, and if the pluton as a whole is a co-magmatic suite, then the analyses of rocks within each group should show a greater degree of correlation. In fig.26 curves are drawn through points re-

Table XIII
Chemical Analyses and Molecular Norms of the Mutton Bay Plutonic Suite

	1	2	3	4	5	6	7	8	9
SiO_2	56.99	63.09	60.49	67.28	61.97	61.47	51.92	62.98	42.70
TiO_2	1.33	0.79	1.08	0.55	0.74	1.00	2.56	0.38	3.46
Al_2O_3	16.59	17.21	17.13	14.66	16.08	15.55	12.52	17.68	7.38
Fe_2O_3	1.54	1.53	1.80	2.66	1.52	1.78	5.57	1.00	7.98
FeO	5.46	1.42	2.28	1.78	4.00	4.22	9.79	2.24	15.24
MnO	0.23	0.13	0.14	0.19	0.25	0.27	0.63	0.14	0.93
MgO	1.27	0.66	1.19	0.50	0.81	0.79	1.42	0.45	4.05
CaO	3.64	1.27	1.90	0.38	1.45	1.78	4.26	1.08	9.66
Na_2O	5.45	5.68	5.33	5.82	6.12	6.16	4.84	6.29	3.22
K_2O	4.84	6.99	6.49	5.47	5.80	5.63	4.36	6.73	2.05
P_2O_5	0.52	0.19	0.35	0.06	0.21	0.22	0.92	0.09	1.52
H_2O	0.60	0.31	0.54	0.27	0.50	0.40	0.63	0.28	1.14
H_2O-	0.07	0.07	0.10	0.07	0.07	0.07	0.09	0.07	0.06
CO_2	0.24	0.38	0.64	0.08	0.09	0.26	0.19	0.22	0.07
F	0.07	0.01	0.04	0.01	0.05	0.06	0.02	0.02	0.53
Cl	0.05	0.04	0.06	0.06	0.05	0.02	0.06	0.06	0.03
S	0.19	0.19	0.12	0.04	0.09	0.10	0.08	0.07	0.13
V_2O_5	0.002	0.001	0.002	0.001	0.002	0.002	0.004	0.001	0.005
BaO	0.99	0.06	0.21	0.004	0.07	0.04	0.04	0.06	0.01
SrO	0.07	0.006	0.04	0.001	0.013	0.006	0.007	0.006	0.005
LiO	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	100.142	100.027	99.932	99.886	99.885	99.828	99.911	99.847	100.170
Q		1.5	0.9	10.9	0.3				
Or	29.0	40.5	38.0	32.0	33.5	33.0	26.5	39.0	13.0
Ab	45.6	50.0	47.5	47.5	52.5	51.5	42.8	52.6	24.4
An	6.5	1.0	3.5						
Ne	2.0						0.7	1.8	3.6
Wo		0.6		0.6	2.0				
Ac				3.6	1.2	2.8	0.8		0.4
Di	6.9					4.7	11.5	2.5	32.5
Hy		2.0	4.0	2.8	5.8	4.1			
Ol	4.3					0.4	5.5	1.3	8.0
Hm		0.4							
Il	1.8	1.2	1.6	0.8	1.0	1.4	3.8	0.6	5.3
Mt	1.7	1.1	1.8	1.5	2.7	0.7	5.7	1.1	8.8
Ap	1.1	0.3	0.8		0.5	0.5	2.1	0.3	3.5
Cc	0.6	1.0	1.6	0.2	0.2	0.6	0.4	0.6	0.2
Py	0.5	0.4	0.3	0.1	0.3	0.3	0.2	0.2	0.3

Analyst : Zoltan Katzendorfer

Samples

1. Coarse-grained green pyroxene syenite (A-30)
2. Coarse-grained foliated pink syenite (T-16-31)
3. Coarse-grained massive pink quartz syenite to syenite - younger phase at Mutton Bay (T-16-39)
4. Medium to coarse-grained greenish to pinkish grey granite (T-21-3)
5. Medium-grained grey syenite porphyry (T-15-32)
6. Medium- to coarse-grained well foliated grey syenite (T-15-16)
7. Coarse-grained dark greenish grey very well foliated syenite - moderately mafic-rich (T-14-1)
8. Coarse-grained greyish orange pink very well foliated syenite (T-14-6)
9. Mafic concentration in coarse-grained greyish orange pink very well foliated syenite (T-13-4)

Note : Niggli molecular norms were calculated according to the rules outlined in Barth (1952, p.79-82).

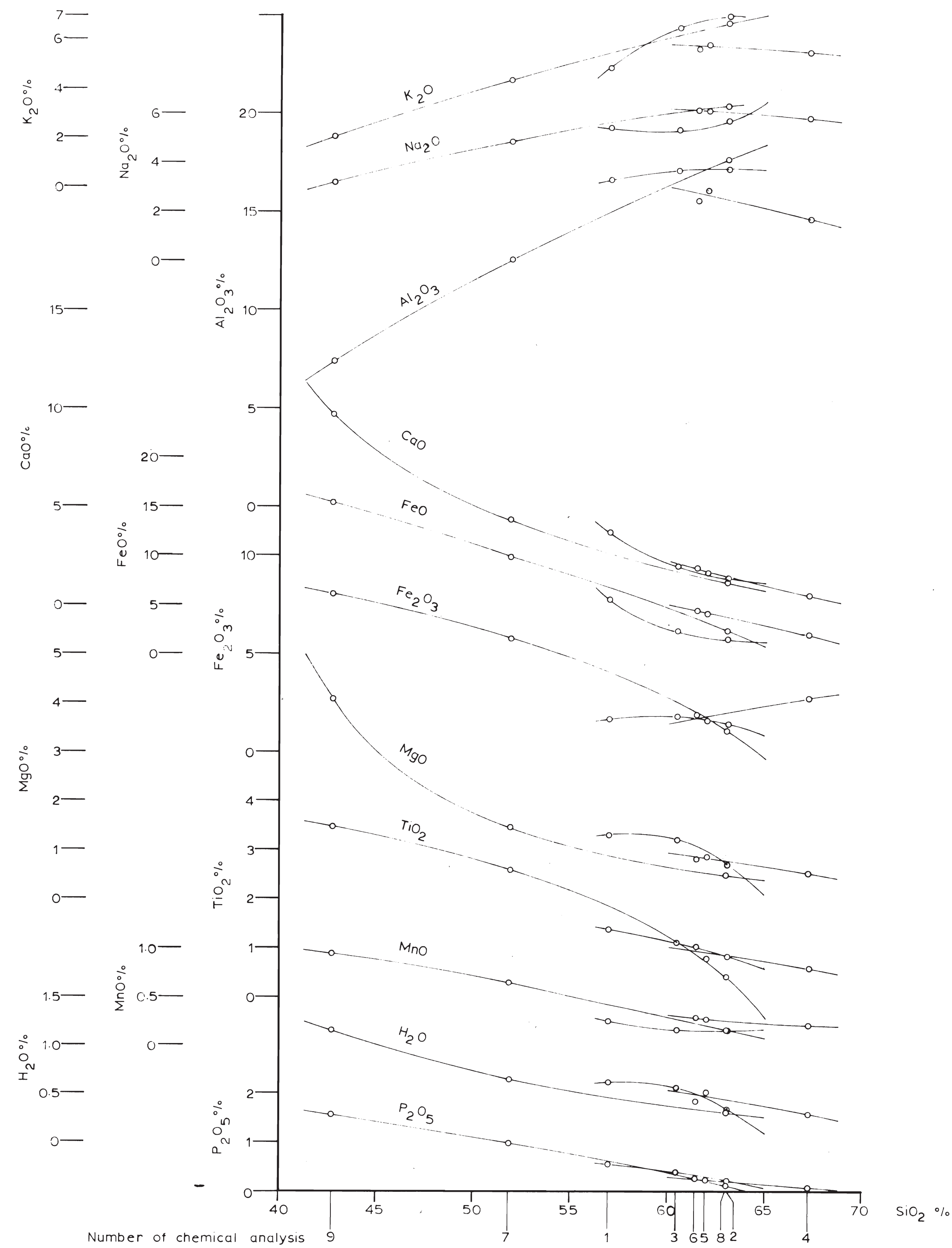


Fig. 26 - Harker variation diagram for the major oxides in rocks of the Mutton Bay intrusion. Weight percent K_2O, Na_2O, Al_2O_3, CaO, FeO, Fe_2O_3, MgO, TiO_2, MnO, H_2O and P_2O_5 plotted against weight percent SiO_2. Curves are drawn through points belonging to the same intrusive group. Analyses 1 - 3 early group, 4 - 6 intermediate group, and 7 - 9 late group. Analysis numbers refer to Table XIII, p. 103

Fig. 26

presenting rocks belonging to the same group. The points of the late group lie on almost straight lines. In the field the late group exhibits differentiation with gradations between rocks similar to all three of the samples analysed.

Lines drawn through points representing rocks belonging to the early group show strong curvature in most cases. The curves may represent a break but three points are not sufficient to prove much more than that the curves are not straight lines. The possibility that the composition of the SiO_2-rich sample of the early group is due to assimilation of country rock by the SiO_2-poor variety was investigated. The increase in SiO_2 is accompanied by a 16-41% decrease in the value of oxides forming mafic minerals and a 0.7% increase in the Na_2O and K_2O values. To achieve the required reduction of the mafic minerals by dilution requires assimilation by the magma of 60% of its weight of a eutectic syenite. Such an anatectic melt might be found at depth. The gneisses at the present level of erosion carry too much quartz to give rise to a suitable anatectic melt. However, such a melt would be suitable if the excess SiO_2 moved to a higher level in the pluton and has been eroded away. The variations observed are more easily explained by differentiation of the magma with separation of the early-formed mafic minerals. The important point is that the large scale contamination of the SiO_2-poor magma by the gneisses to form the silica-rich variety is unlikely, and the three samples can form a co-magmatic series

There is little one can say about the lines through points representing the intermediate group of rocks. The points could lie on smooth curves. However, they do not lie on either of the curves of the other groups, and clearly belong to a separate series.

The three groups overlap in composition and each group represents a period in which the parent magma had a certain composition and differentiated into the various rocks of the group. The variation in the parent magma may have resulted from a number of processes, including contamination, differential melting, and crystallization differentiation. It is possible, from a study of the curves for the individual groups, to compare the group variations or trends. With respect to the other groups the early group is high in Al_2O_3 and K_2O, the intermediate group is high in SiO_2, FeO, MnO, MgO, CaO, Na_2O, P_2O_5, and H_2O, and the late group is high in TiO_2.

Variation of BaO and SrO with respect to age

When BaO and SrO are plotted against the relative age of the rock as in fig.27 there is a concentration of both oxides in the early rocks and a decrease in the younger rocks. This is found in the Oslo eruptive rocks (Oftedal, 1958) and the Kûngnât intrusion in South Greenland (Upton, 1960). The BaO and SrO variation results from the removal of these oxides from the magma by the early crystallizing felspars, and, as suggested by Oftedal (1958), is a function of temperature of crystallization. There are two anomalous values which do not fit on the curve. One is the granite which is a rock crystallized from a residual melt rich in SiO_2 and presumably depleted in BaO and SrO. The other is the early foliated syenite which is anomalous in other respects. Its BaO and SrO values suggest that

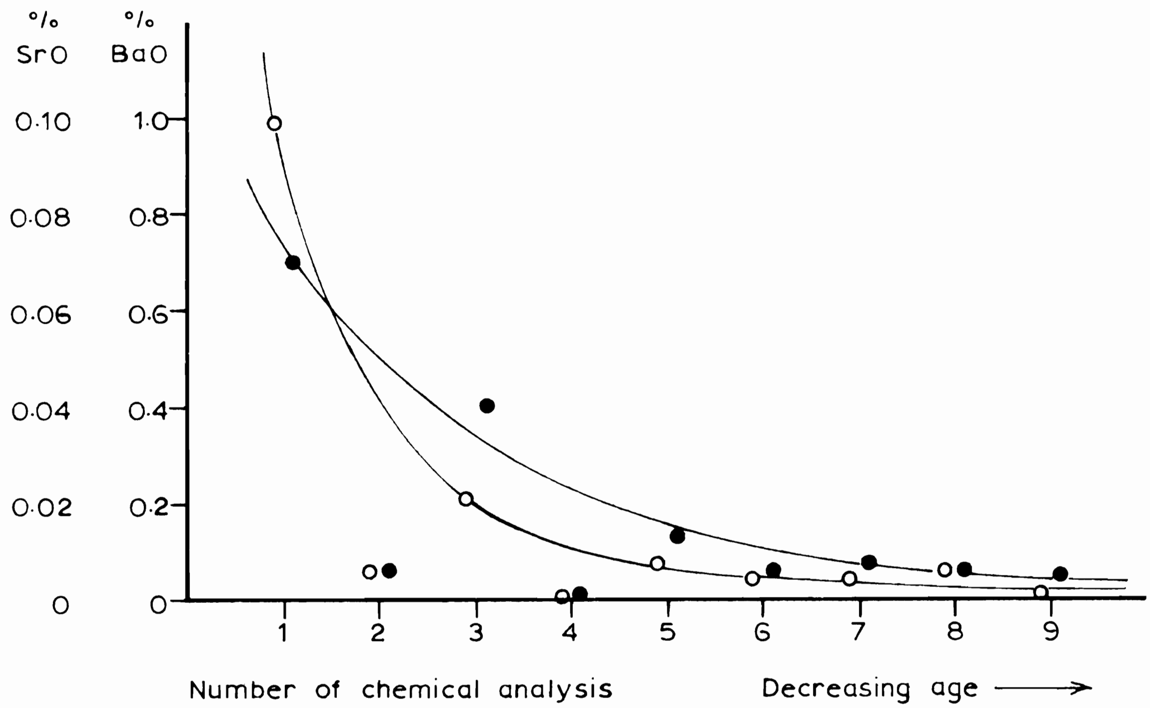


Fig. 27 - Variation diagram for SrO (•) and BaO (o) of the Mutton Bay intrusion. Weight percent oxide plotted against relative age of the rock. Numbers of chemical analyses refer to Table XIII (p.103). 1-3 belong to the early group, 4-6 to the intermediate group, and 7-9 to the late group.

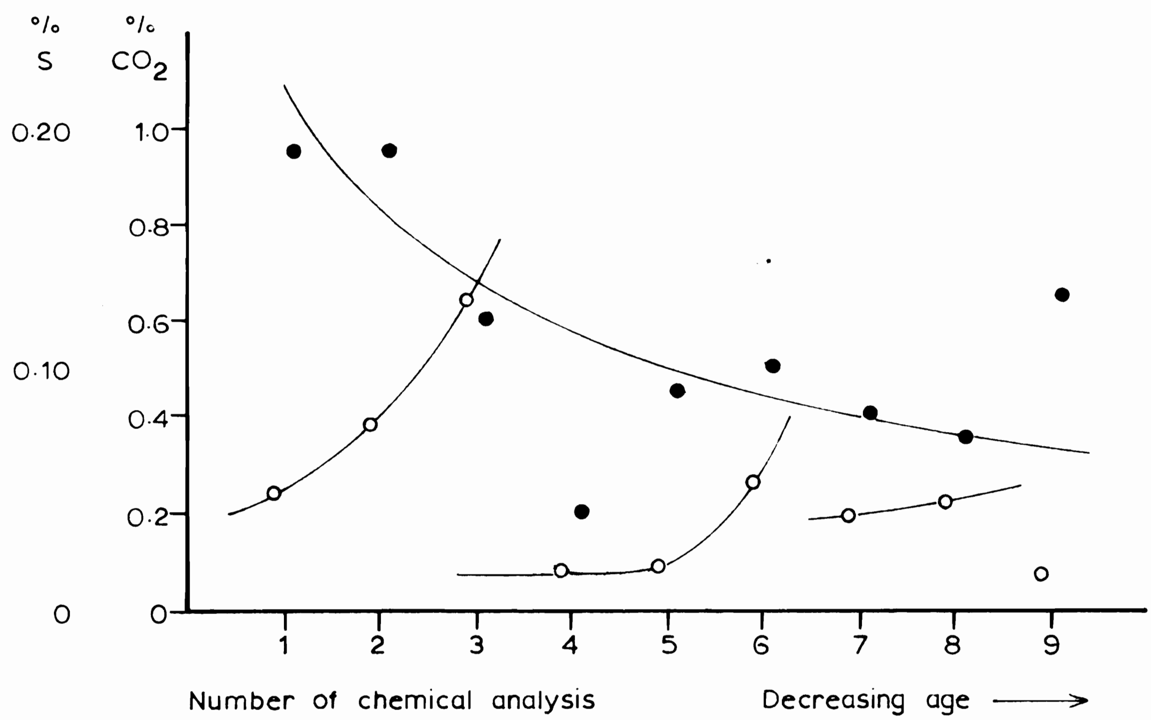


Fig. 28 - Variation diagram for S (•) and CO_2 (o) of the Mutton Bay intrusion. Weight percent S and CO_2 plotted against relative age of the rock. Numbers of chemical analyses refer to Table XIII (p.103). 1-3 belong to the early group, 4-6 the intermediate, and 7-9 to the late group.

it might belong to the late group, but a more likely explanation is that the early foliated syenite represents a residual melt of perhaps the older coarse-grained pink syenite at Mutton Bay. It contains less early mafic minerals than the latter. Contacts between the two were not seen and it is possible that the foliated variety represents the late crystallizing roof of a cone sheet. The early foliated syenite reached its present position as a crystal mush, indicating that the temperature of the magma was lower than that when the massive pink syenites were emplaced.

Variation of CO_2 and S with respect to age

CO_2 and S are plotted against relative age in fig.28. Concentration of CO_2 and S in the early group indicates a build-up of volatiles that could not escape. The younger intrusives tended to lose more of the volatile elements, suggesting that they reached the surface or intruded fractures that reached the surface. The granite is anomalously low with respect to S, showing that the sulphides probably crystallized early, and the mafic segregation of the late group is anomalously high in S for the same reason. CO_2 increases within each group and the mafic segregation of the late group is anomalous as expected. It is important that the early foliated pink syenite is not anomalous in the case of CO_2 and S, showing that it does not belong to the late group.

Variation of F and Cl with respect to normative apatite

The halides appear to be tied up in apatite and show a fairly good correlation with normative apatite (fig.29). Fluorite was not seen in the plutonic rocks but only in late veins and dykes. The one low halide value which lies off the curve is not necessarily anomalous as the halides can be replaced in apatite by OH or O. There is no correlation between halides and the relative age of the intrusion as with S and CO_2.

Variation of total alkali with respect to SiO_2

The total alkalis of the Mutton Bay plutonic rocks vary with respect to SiO_2 like the larvikite, nordmarkite, and nordmarkite-ekerites of the Oslo region (fig.30). The silica-poor larvikite does not contain oligoclase, but the other does and is a true larvikite according to Barth's (1945) definition. The nordmarkites of Mutton Bay correspond very closely with those of the Oslo region as does the nordmarkite-ekerite.

Variation of $MnO/FeO + Fe_2O_3$ with respect to age

Abramovich et al (1963), from a study of the Mn/Fe (total) ratios in igneous rock series, suggest that the ratio may be useful in assigning rocks to igneous series and placing the series itself in a sequence of formations. According to Mason (1960) Mn in igneous rocks replaces ferrous iron and a relative increase in the Mn : Fe ratio has been noted in later differentiates, indicating that the larger size of the Mn ion causes it to be admitted to ferromagnesian minerals. In the Lovozero intrusive of the Kola Peninsula, Gerasimovskii and Belyayev (1963) found a Mn enrichment in successive intrusive stages.

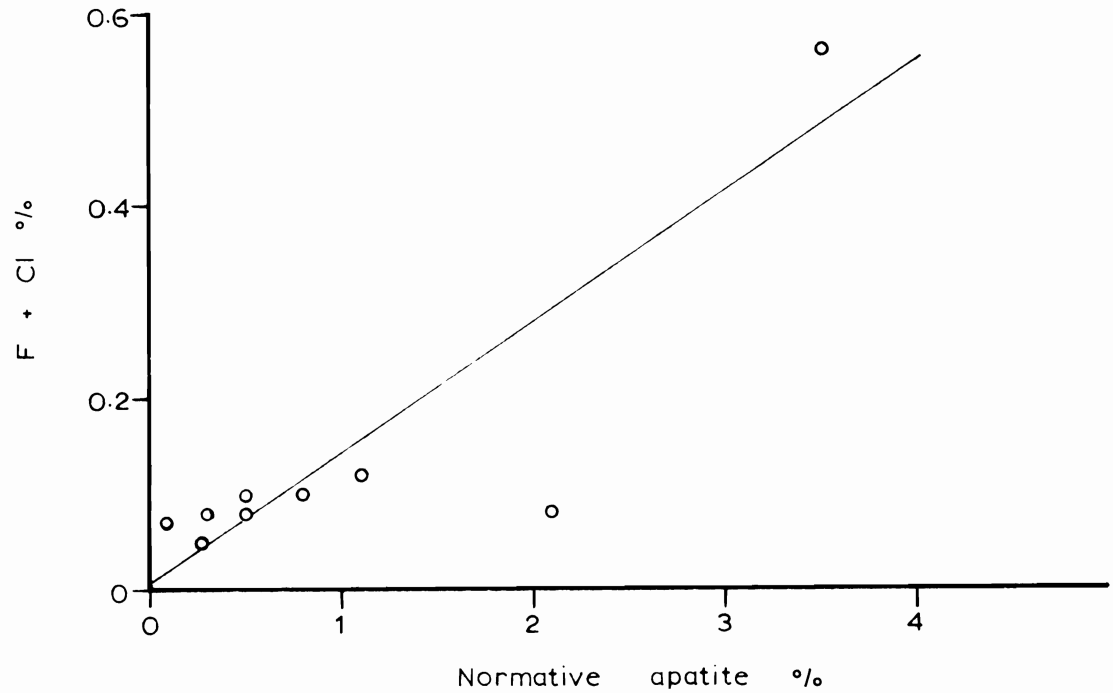


Fig. 29 - Variation diagram for total halides (F + Cl) of the Mutton Bay intrusion. Weight percent halide plotted against normative apatite.

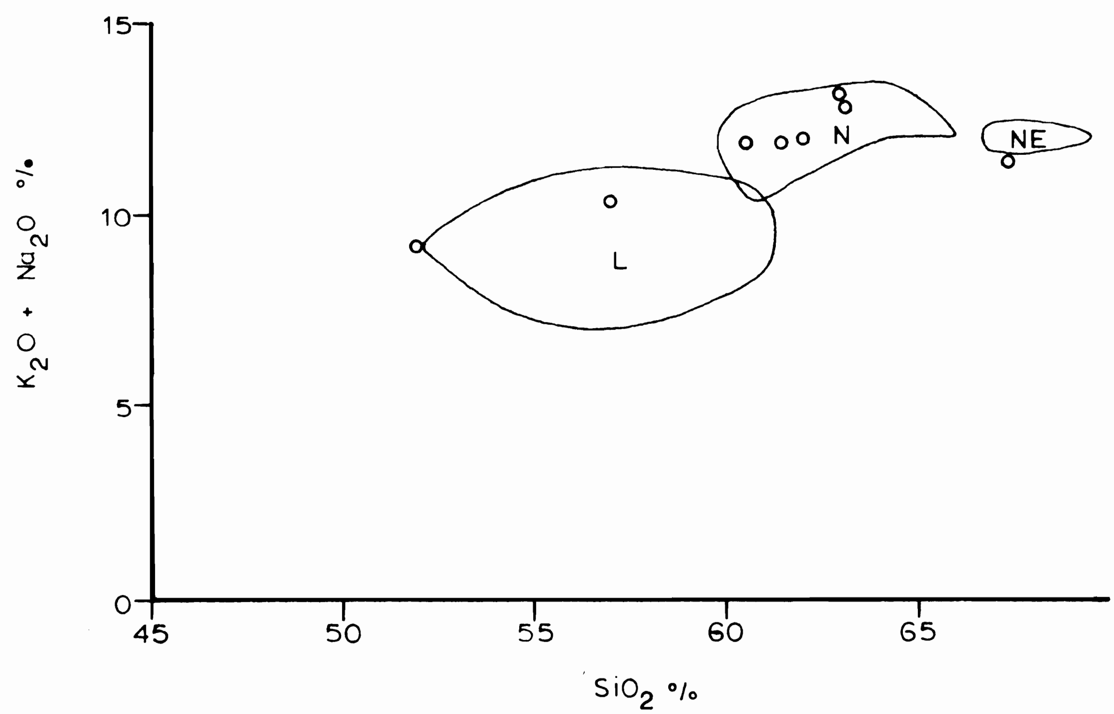


Fig. 30 - Variation diagram for total alkalis ($Na_2O + K_2O$) of the Mutton Bay intrusion. Weight percent alkalis plotted against weight percent SiO_2. Range in values for the larvikite (L), nordmarkite (N), and nordmarkite-ekerites (NE) of the Oslo region (after Barth, 1945) are plotted for comparison.

When the $MnO/FeO + Fe_2O_3$ ratios of the Mutton Bay rocks are plotted against relative age there is a sharp break between the early group and the later groups (fig.31). The anomalous early foliated sample is explained as being a late crystallizing differentiate of a member of the early group and therefore anomalous with respect to the pluton as a whole. Its anomalous BaO and SrO values were explained the same way.

Variation of MnO with respect to FeO

Wager and Mitchell (1951) showed that the tendency for Mn" and Fe" to enter crystal lattices are about equal, so the ratios of Mn"/Fe" in a differentiated sequence should be equal.

Fig.32 is a plot of MnO against FeO for the Mutton Bay intrusive. A straight line is obtained which passes through the origin. Two values lying above the curve are late local differentiates high in SiO_2 and with high Fe^{+++}/Fe^{++} ratios. The point lying below the curve has a low Fe^{+++}/Fe^{++} ratio and is the oldest intrusive phase. This suggests that the oxidation state of the Fe increases in the late crystallizing fraction of magma and that the first intrusion of magma was less oxidized than the ones that followed. When MnO is plotted against $FeO + Fe_2O_3$ there is a greater degree of correlation (fig.33) which supports the above idea and points to the Fe in the parent magma being essentially in the ferrous state.

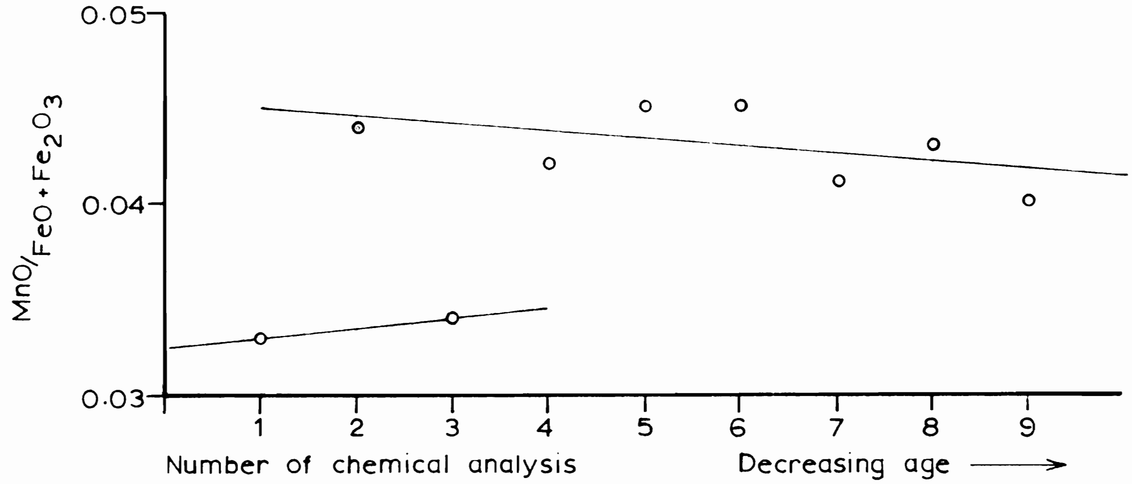


Fig. 31 - Variation diagram for the $MnO/FeO+Fe_2O_3$ ratios of the Mutton Bay intrusion. Ratios are plotted against relative age of the rocks, and the numbers of chemical analyses refer to Table XIII (p.103)

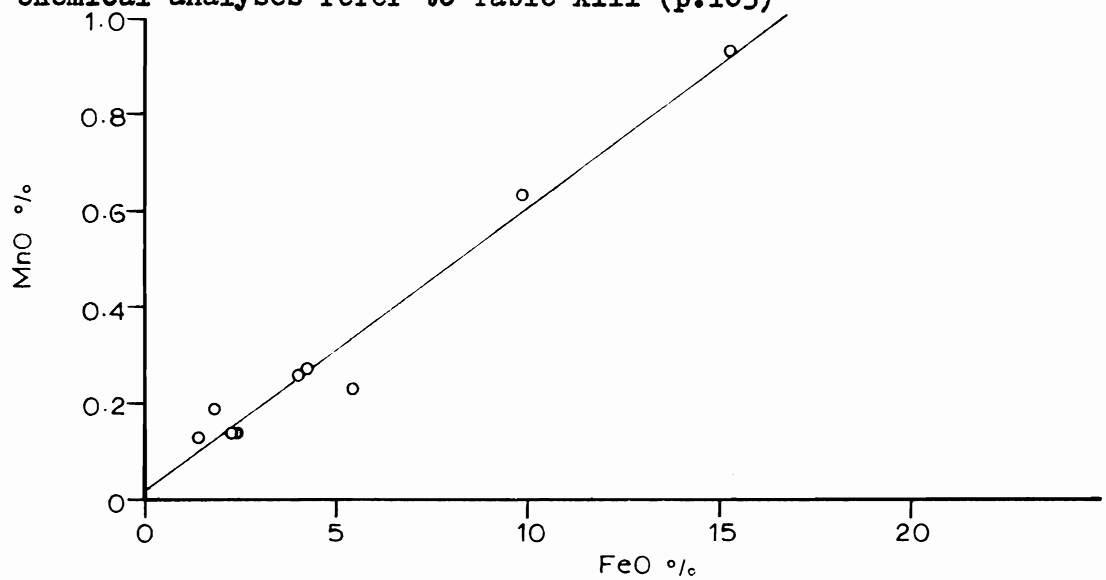


Fig. 32 - Variation of MnO with respect to FeO for the Mutton Bay intrusion Weight percent MnO plotted against weight percent FeO.

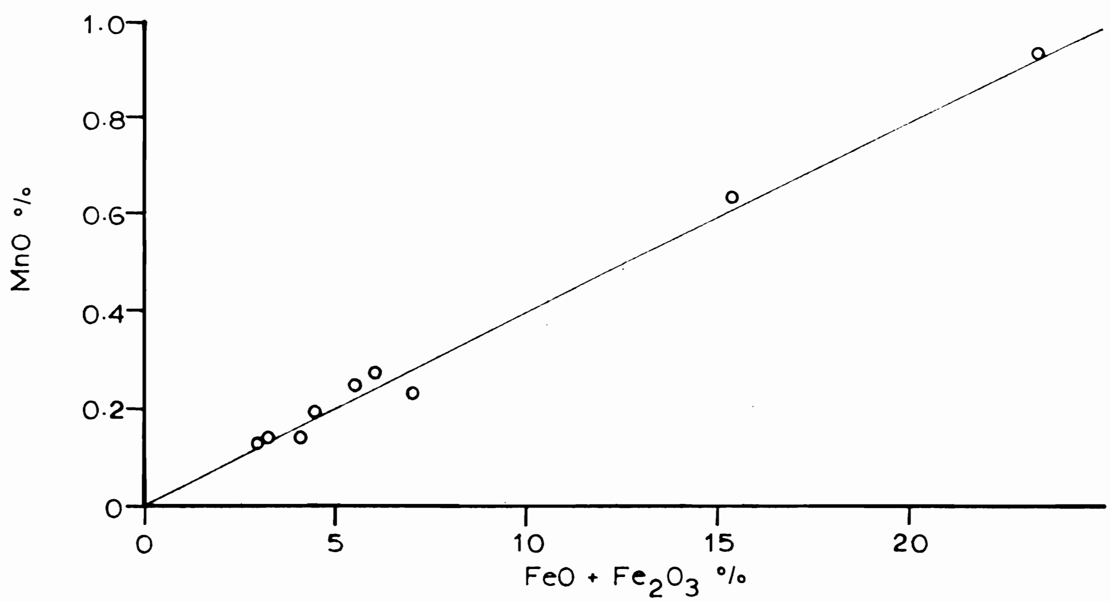


Fig. 33 - Variation of MnO with respect to $FeO + Fe_2O_3$ for the Mutton Bay intrusion. Weight percent MnO plotted against weight percent $FeO + Fe_2O_3$.

Variation of $TiO_2/FeO + Fe_2O_3$ with respect to age and SiO_2

Abramovich and Vysokoostrovskaya (1964) found that rocks of the same petrographic type but from different complexes have different Ti/Fe ratios. The Ti/Fe ratio of a single complex was found to increase as SiO_2 decreased.

When $TiO_2/FeO + Fe_2O_3$ ratios of the Mutton Bay rocks are plotted against relative age there is a sharp break between the early and the later groups (fig.34). The early rocks have a higher relative TiO_2 content suggesting contamination by assimilation of country rock. If the ratios of the later rocks are plotted against SiO_2 there is a general increase of the ratio with decreasing SiO_2 content (fig.35). It is interesting that sample No.2, which was anomalous with respect to Mn/Fe ratios and Ba and Sr values, is clearly related to the early group in this case.

Variation of Fe_2O_3/FeO, Na_2O/CaO, FeO/MgO, and $FeO + Fe_2O_3/MgO$ with respect to SiO_2

H_2O has an oxidizing effect on ferrous iron, oxidizing it to ferric iron and so resulting in the precipitation of large amounts of magnetite as an alternative to ferrous silicates such as fayalite (Goldschmidt, 1954, p.28). In the Mutton Bay pluton the Fe_2O_3/FeO ratio increases with SiO_2 content especially if the groups are considered separately (fig.36). While the present H_2O content decreases with SiO_2 content, it was probably enriched at the time of crystallization but was lost because there was nothing to hold it. Increase in water would have caused the oxidization of FeO.

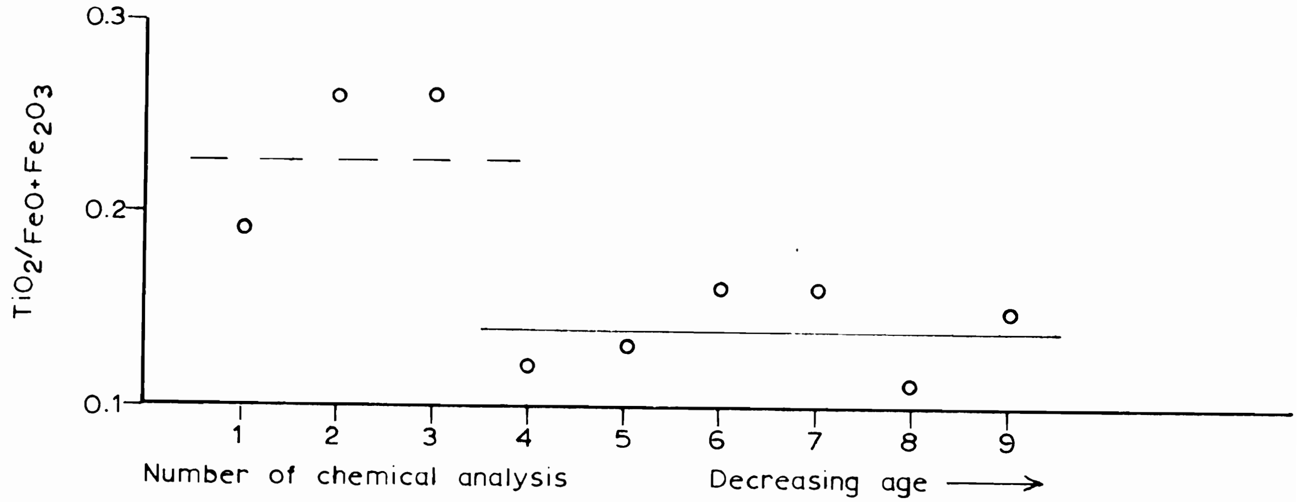


Fig. 34 - Variation diagram for the $TiO_2/FeO + Fe_2O_3$ ratios of the Mutton Bay intrusion. Ratios are plotted against relative age of the rocks and the numbers of chemical analyses refer to Table XIII (p.103).

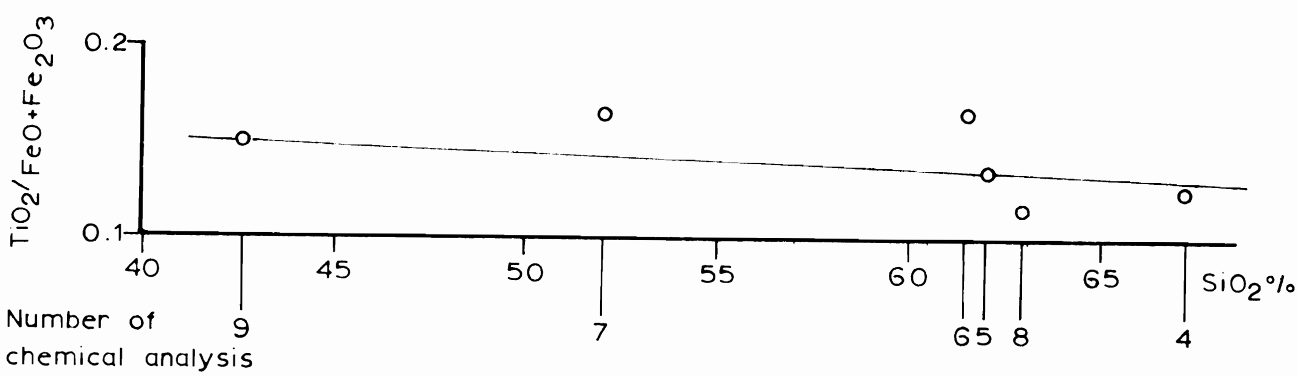


Fig. 35 - Variation of $TiO_2/FeO + Fe_2O_3$ with respect to weight percent SiO_2. Analyses 4-6 intermediate group ; 7-9 late group. Analyses numbers refer to Table XIII (p.103).

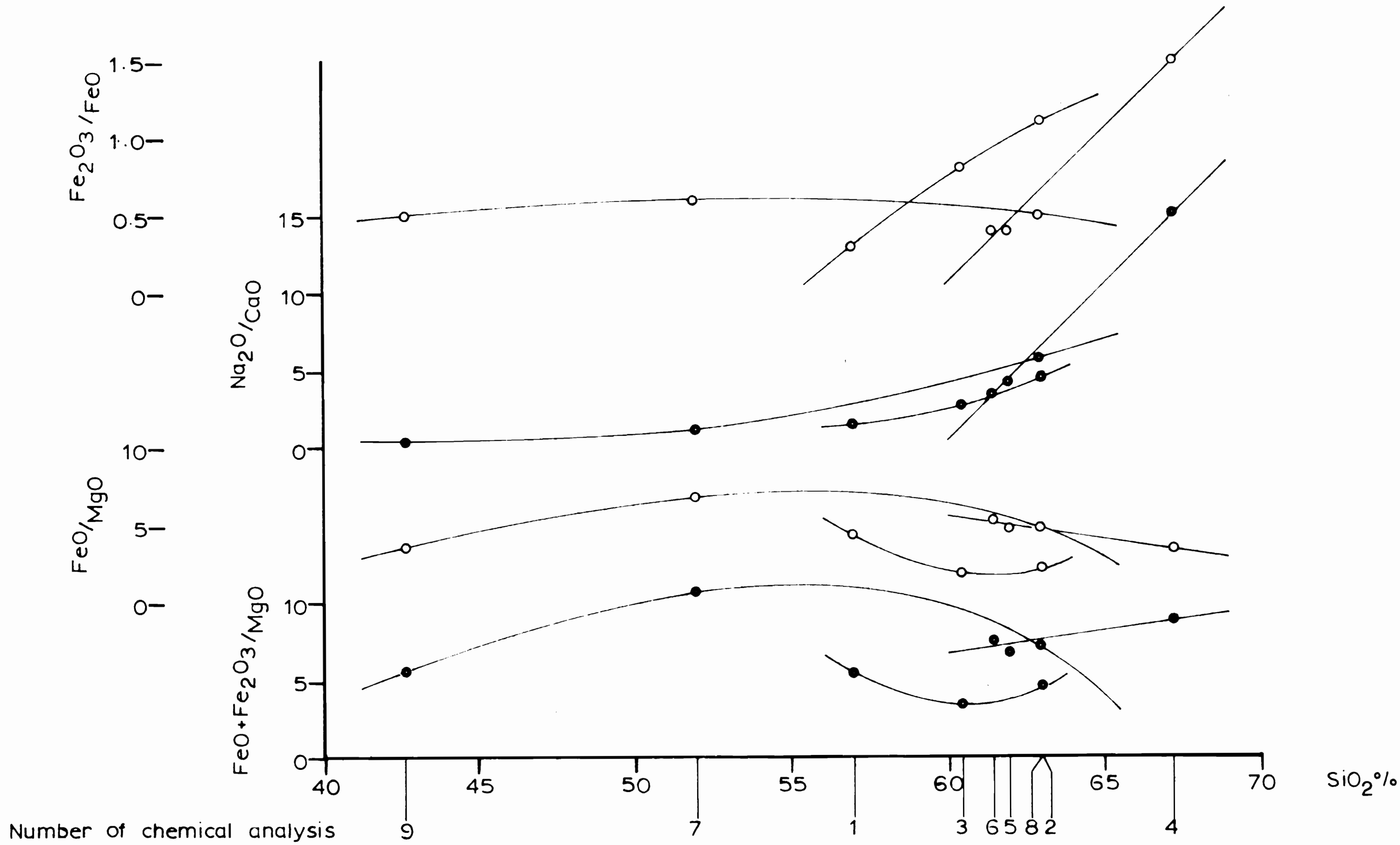


Fig. 36 - Variation of Fe_2O_3/FeO, Na_2O/CaO, FeO/MgO, and $FeO + Fe_2O_3/MgO$ with respect to weight percent SiO_2. Curves are drawn through points belonging to the same intrusive group. Analyses 1-3 early group, 4-6 intermediate group, and 7-9 late group. Analysis numbers refer to Table XIII

Na_2O/CaO ratios increase with increasing SiO_2 content as would be expected in a differentiated sequence. There are irregularities which are eliminated if the groups are considered separately.

It is important that neither FeO/MgO or $FeO + Fe_2O_3/MgO$ ratios show any variation with SiO_2 content. The lack of correlation with SiO_2 content indicates that the mafic ratios were constant and that any variation of the mafics was of a mechanical nature. The anomalous samples are explained by the addition and subtraction of the late Fe-rich liquid respectively. The possibility that the late liquids, that were last to crystallize, were contaminated with MgO from the country rock gneisses is unlikely.

<u>Coefficient of variation of the major oxides</u>

Tsarovskii (1963) attempted to distinguish qualitative differences between rocks of identical mineralogy but different origin on the basis of the coefficient of variation. Components with the same coefficient of variation $\underline{v}$ $\left(\underline{v} = \frac{S \times 100}{\bar{x}}\right.$, where S is standard deviation and $\bar{x}$ is the arithmetic mean) are believed to have been involved in the same differentiation process. The coefficient of variation of the major oxides of the Mutton Bay intrusion, both with and without the mafic segregation excluded, and of the larvikites and nordmarkites of the Oslo region are presented in Table XIV.

The oxides of the Mutton Bay intrusion with the lowest coefficient of variation, SiO_2, Al_2O_3, K_2O, and Na_2O, are those con-

Table XIV

Coefficient of variation v of the major oxides of the Mutton Bay intrusion and of the Oslo nordmarkites and larvikites

Oxide	Mutton Bay (excluding mafic segregation)		Mutton Bay (including mafic segregation)		Nordmarkites Oslo Region		Larvikites Oslo Region	
SiO_2	7.06	(1)	12.17	(1)	1.77	(1)	3.54	(1)
Al_2O_3	9.93	(1)	20.49	(1)	2.94	(1)	6.50	(1)
Fe_2O_3	62.15	(3)	79.00	(3)	30.35	(2)	33.41	(2)
FeO	66.27	(3)	83.68	(3)	43.60	(2)	19.01	(2)
FeO + Fe_2O_3	61.59	(3)	-		-		-	
MnO	61.69	(3)	80.04	(3)	68.36	(2)		
MgO	38.32	(2)	82.56	(3)	33.79	(2)	38.73	(2)
CaO	62.58	(3)	56.14	(2)	49.79	(2)	12.23	(1)
Na_2O	8.05	(1)	16.46	(1)	7.55	(1)	6.46	(1)
K_2O	15.31	(1)	26.53	(1)	6.45	(1)	12.05	(1)
P_2O_5	82.69	(4)	100.50	(4)	161.20	(3)	70.17	(3)
TiO_2	89.29	(4)	73.02	(3)	54.30	(2)	25.58	(2)

Note

Values for the various oxides have been grouped as indicated by the numbers in brackets, (1) indicating a low coefficient and (4) high coefficient of variation

Values for the rocks of the Oslo region are calculated from analyses given by Barth (1945).

stituting the felspar which do not vary much in amount or composition. Lower values are found when the mafic segregation is excluded. FeO, Fe_2O_3, total iron oxide, MnO, and CaO have high coefficients as these oxides are found in the ferromagnesian minerals that varied in amount by gravity settling and filter pressing processes. MgO has a similar high value when the mafic segregation is included, but a much lower value when it is not. MgO is believed concentrated in the early crystallizing pyroxene and olivine which, because of the early crystallization and interference of the perthite, were not subject to strong concentration by gravity settling. The mafic segregation analysed is an exception. The amphiboles and biotites crystallized from late liquids which were subject to concentration by filter pressing. The highest coefficient of variation is found for P_2O_5 and TiO_2 though the TiO_2 is lower when the mafic segregation is included. These oxides are concentrated in the very first crystals to form and were subject to concentration by gravity settling before the perthites could interfere.

Coefficient of variation values for nordmarkites and larvikites of the Oslo region are given for comparison. The picture is very much the same. TiO_2 has a lower coefficient than the P_2O_5 , suggesting that it is contained essentially in the pyroxene, amphibole, and biotite rather than in the oxides. The values in general are lower than those of the Mutton Bay intrusion, probably because the analyses are of more homogeneous groups of rocks.

MINERALOGY OF THE PLUTONIC ROCKS

Felspar

Felspar of the Mutton Bay intrusion is almost entirely perthitic. Rare oligoclase (An_{18}) is found as corroded cores of perthitic felspar crystals in the coarse-grained massive green pyroxene syenite (fig.37). The colour of the felspar is the same as that of the rock, being green, red, or grey.

Microperthite dominates but cryptoperthite is common (fig.38). The degree of un-mixing is most intense around the borders of grains and varies with the different rock types. The perthite crystals often show simple Carlsbad twinning and commonly have swapped boundaries (fig.39).

A number of rock types, particularly the porphyritic varieties, contain felspar crystals with corroded perthite cores believed to be xenocrysts, surrounded by a later growth of perthite. In hand specimens these crystals have dark cores and light rims. There is usually a difference in the amount of un-mixing in the core and border zones. The cores may or may not be full of mafic inclusions (fig.40), and in some cases mafic inclusions are confined to the border zone (fig.41). The inclusions generally increase in size towards the border.

The plagioclase component of the perthite is low albite. It is finely twinned (fig.42) and, in patches sufficiently large, the composition was determined by measuring the extinction in sections perpendicular to 010 and 001. Since exsolution is generally best developed around the borders of grains, there is danger that in a zoned felspar the best exsolved plagioclase would not be represent-

Fig. 37 - Microperthite with a core of oligoclase in coarse-grained massive green pyroxene syenite. Crossed nicols. X 35.

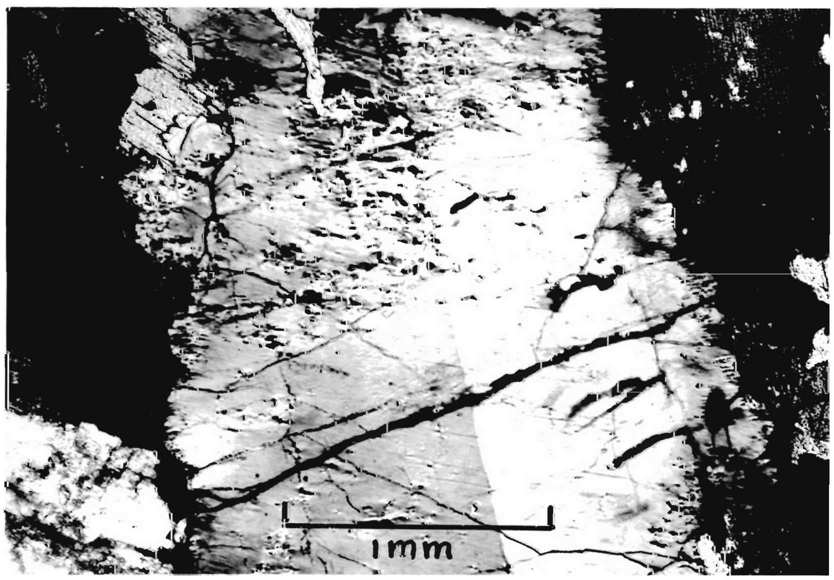


Fig. 38 - Cryptoperthite with microperthite patches. Crystal shows simple twinning.
Crossed nicols. X 35.

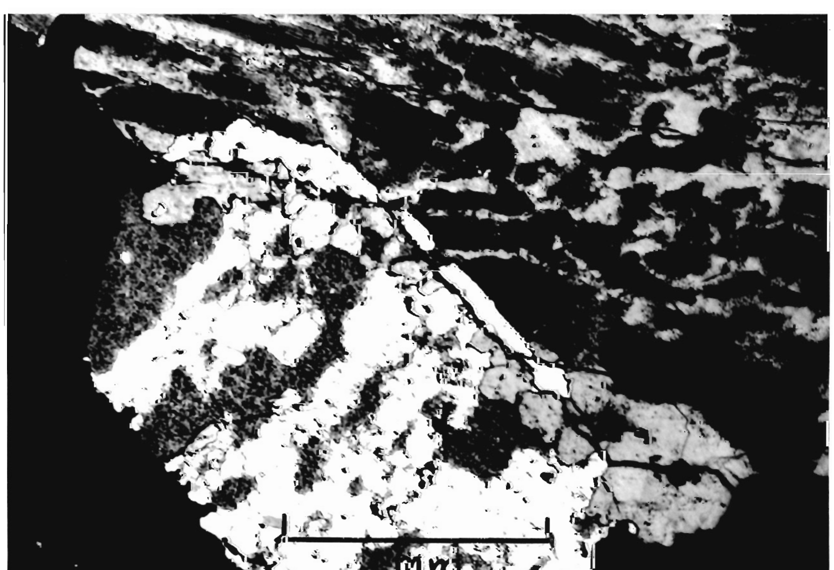


Fig. 39 - Adjacent crystals of microperthite with swapped boundaries. Crossed nicols. X 70.

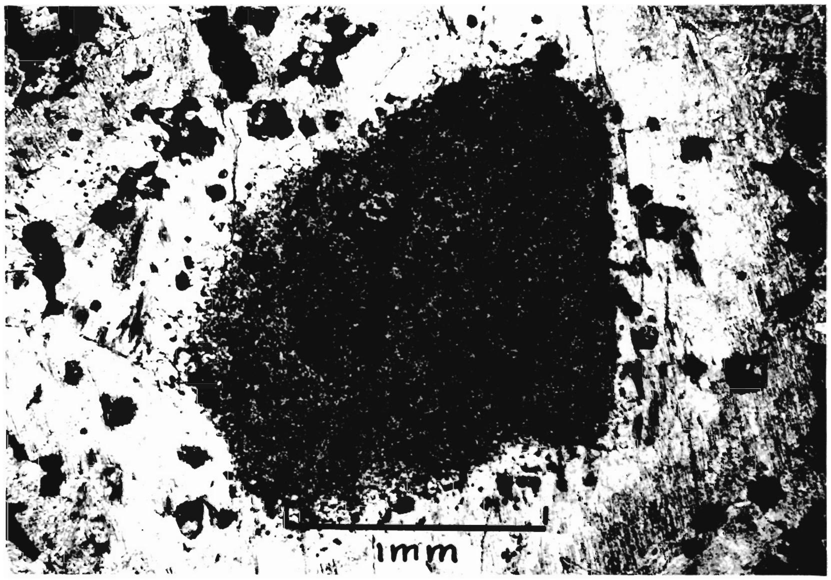


Fig. 40 - Microperthite surrounding a corroded core of chloritized felspar. Microperthite contains inclusions that increase in size towards the crystal boundaries.
Crossed nicols. X 35.

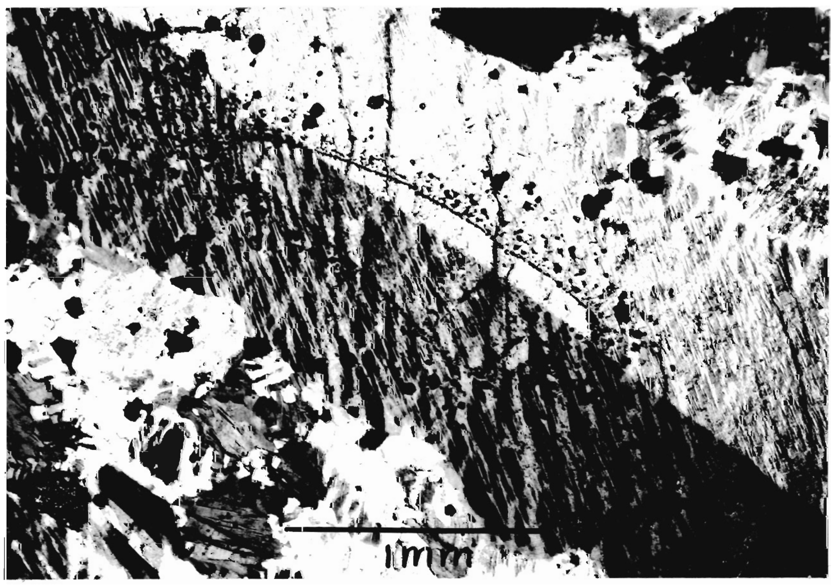


Fig. 41 - Clear corroded core of microperthite surrounded by microperthite with inclusions that increase in size towards the crystal boundaries.
Crossed nicols. X 35.

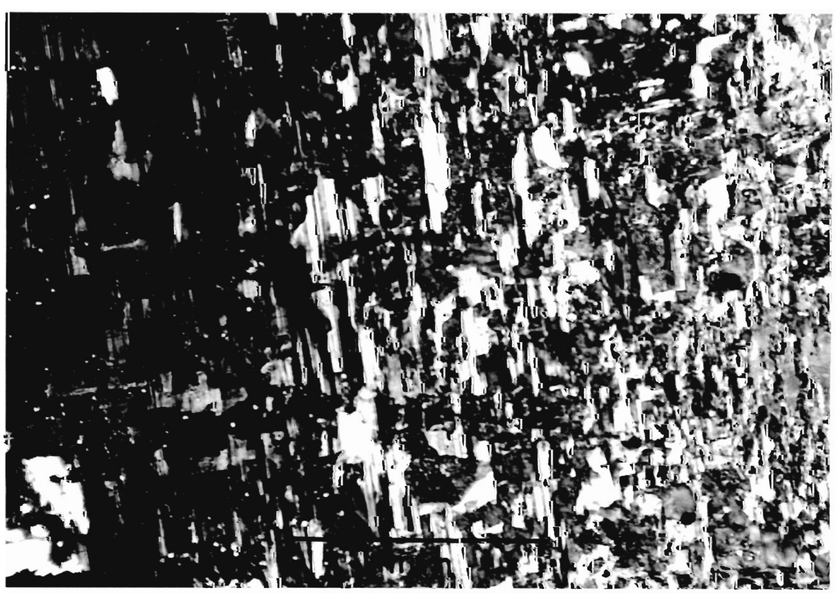


Fig. 42 - Twinning in the plagioclase component of a well-exsolved microperthite.
Crossed nicols. X 35.

ative. A range in composition of about 3 percent An was observed in some specimens. Oil immersion techniques on powdered material are therefore not reliable as border material will dominate. Each determination was made on a minimum of three grains. Borders of grains were avoided where possible and care was taken not to measure plagioclase that was not intergrown with potash felspar. The aim was to measure the most calcic plagioclase exsolved in each thin section.

The anorthite content of exsolved plagioclase of samples arranged according to their established relative age is plotted in fig.43. Each of the three major groups shows a variation. In both the early and intermediate groups the exsolved plagioclase becomes more sodic in successive intrusions. In the late group it does the reverse and apparently becomes more calcic.

A mafic-rich hybrid of early coarse-grained green syenite included in early coarse-grained pink syenite contains exsolved plagioclase with the same composition as the host rock and the normal coarse-grained green syenite. Concentration of heavy minerals in the early group was apparently not accompanied by a variation in the composition of the felspar. In the late group differentiation has been of a different sort. In each of the sub-groups the mafic concentrations contain a soda-rich exsolved plagioclase (fig.43). These mafic segregations were due partly to gravity and partly to flow differentiation, so that early mafic minerals are concentrated in the lower contact zones with late liquids including late felspathic components.

An interesting feature from the point of view of rock colour

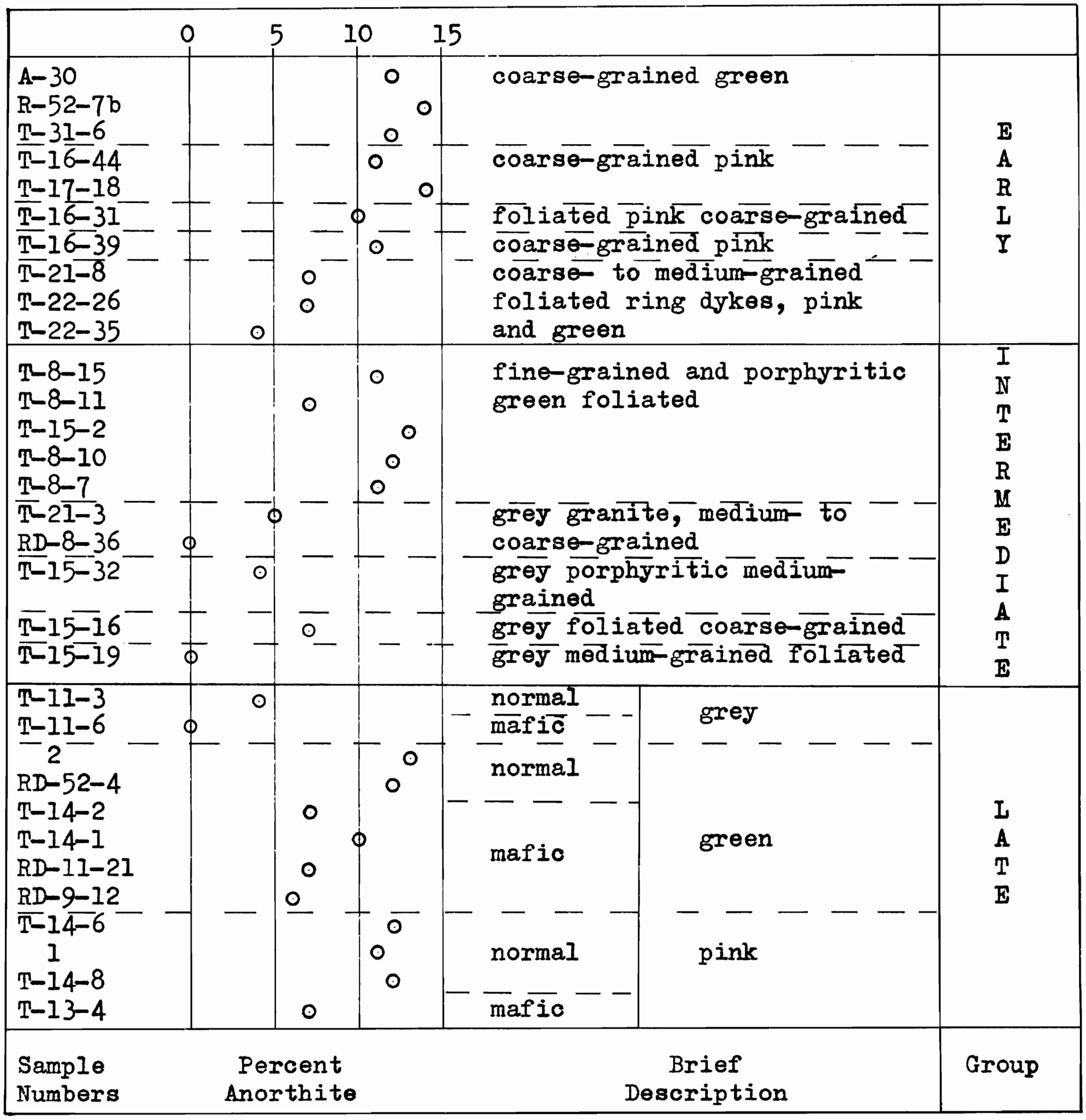


Fig. 43 - Anorthite percentage of exsolved plagioclase in perthite plotted against the relative age of the rock types. Points between broken lines represent equivalent age or their relative age is not known. The late group is divided into normal and mafic-rich varieties.

is that all the grey rocks contain exsolved plagioclase with low anorthite content.

The potash felspar component of the perthite is variable in its properties and it is possible in the same grain to find two optically different varieties. The potash felspar of the early members of the intermediate group and all members of the early group, except for the massive green syenite at the centre and the massive green quartz syenite at the contact of the intrusion, have a low $2V_x$ ($< 60^{\circ}$), whereas the potash felspar of the later rocks have a high $2V_x$ ($> 60^{\circ}$).

$2V_x$ of the potassic phase of a perthite is affected both by the structural state and the composition of the exsolved phases. If $2V_x$, structural state (see below), and bulk composition (p.132) of the perthites of the Mutton Bay intrusion are compared it is evident that composition is the controlling factor in this case and all perthites with an Ab/Or ratio greater than 55/45 have $2V_x$ = $> 60^{\circ}$. A **sample** with Ab/Or ratio of 55/45 contains potash felspar with $2V_x$ both greater and less than 60°.

<u>Determination of obliquity $\triangle$ (percent) of potash felspar, structural type (high or low) of plagioclase, and type (monoclinic or triclinic) of potash felspar in microperthites</u>

Because of the similarity of rock types with those of the Loch Ailsh intrusion, the author followed the method used and described by Parsons (1965) for the determination of the obliquity of the potash felspar, the structural type of the plagioclase, and the type of potash felspar in the perthites. In brief, measurements are made with an x-ray diffractometer on powdered felspar, using CuK_{α} radiation.

Obliquity of triclinic potash felspar can best be established by measuring the separation of the 131 and $1\bar{3}1$ reflections (Laves, 1952). In sodic perthites Parsons found the $1\bar{3}1$ reflection of microcline masked by the $1\bar{3}1$ reflection of low albite. However, he found that he could divide the specimens into six groups on the basis of the shape of the microcline 131 - $1\bar{3}1$ reflections. By roughly comparing with these six groups he could classify all the potash felspars of the intrusive, and his three syenites form a series on this basis. Steiger and Stanley (1967) present diffractometer traces for artificial mixtures of orthoclase and microcline. Parsons' type 1 corresponds to a mixture about $Or_{40}Mi_{60}$, types 2-4 correspond to $Or_{40}Mic_{60}$ to $Or_{15}Mic_{85}$, and types 5 and 6 to $Or_{15}Mic_{85}$ to Mic_{100}.

Direct measurement of the obliquity values is impossible because of superimposed Na-phase reflections, so a modification was devised. Measurement of the position of the single resolved 131 reflection offers a method of estimating obliquity since the 131 - $1\bar{3}1$ doublet splits linearly from an extrapolated 131 reflection position at $29.87^{\circ}2\theta$ for potash felspar of zero obliquity. As an internal datum for measurement of the movement, the measurement of the $02\bar{2}$ reflection of low albite at $30.48^{\circ}2\theta$ (Smith, 1956) was chosen. It may be influenced by the low albite $0\bar{4}1$ reflection but was resolved. In the transition from low to high albite the $02\bar{2}$ reflection changes position very little and any deviation can be cross-checked by considering the 131 reflection of albite.

Percent obliquity of potash felspar is calculated by taking the angle 2θ albite $02\bar{2}$ - 2θ orthoclase 131 as zero obliquity and the maximum value of 2θ albite $02\bar{2}$ - 2θ microcline 131 of the Mutton Bay felspars as 100 percent obliquity. The latter value is the same as that used by Parsons and which he considered not significantly different from maximum microcline.

The obliquity, structural type of the albite, and type of potash felspar of 56 samples belonging to various units of the pluton were determined (Table XV), and the more important features of the Mutton Bay intrusion perthites are the following :

a) The plagioclase component of the perthite is low albite with angles 2θ albite $02\bar{2}$ - 2θ albite 131, clustering closely around the average value 0.728 with a range from 0.62 - 0.89.

b) Angles 2θ albite $02\bar{2}$ - 2θ orthoclase 131 vary between 0.53 and 0.68. 0.68 was the largest angle found by Parsons (1965).

c) The angle 2θ albite $02\bar{2}$ - 2θ microcline 131 lies between 0.88 and 1.09 which corresponds very well with those of Parsons.

d) From the study of diffractometer traces and comparison with the 6 potash felspar types of Parsons, certain features are evident :

(1) Type 1, dominantly monoclinic potash felspar, is confined to the perthites of the massive varieties, including pegmatites, of the early group. Potash felspar in perthites of four foliated varieties and two massive varieties of the early group correspond to types 2,4,5, and 6.

(2) The potash felspar in perthites of the intermediate and late groups corresponds to types 2-6.

(3) Perthites of six specimens taken across a differentiated sequence of the late group showed no change in type of potash

Table XV

Angles 2θ Ab $02\bar{2}$ - 2θ Ab 131, 2θ Ab $02\bar{2}$ - 2θ Or 131, 2θ Ab $02\bar{2}$ - 2θ Mic 131, percent obliquity of potash felspar and type of potash felspar determined on felspars of the Mutton Bay intrusion

Sample Numbers	Foliated - f Massive - m	2θ Ab $02\bar{2}$ - 2θ Ab 131	2θ Ab $02\bar{2}$ - 2θ Or 131	2θ Ab $02\bar{2}$ - 2θ Mic 131	Obliquity of microcline in percent	Type of potash felspar
Early Group						
A-30	m	0.89	0.57	1.04	88	1
T-31-6	m		0.62	1.09	100	1
T-16-39	m	0.73	0.62	1.07	95	1
T-16-44	m	0.71	0.66			1
T-21-9	m	0.72	0.63			1
R-52-7(b)	m	0.88	0.53			1
T-21-8	m	0.69	0.62			1-(2)
T-17-18	m	0.72	0.69	0.96	68	5
L-1-1	f	0.85	0.61			1
T-16-31	f	0.73		0.88	49	4
T-22-26	f	0.72	0.62			2
T-22-23	f	0.70		0.96	68	6-5
T-22-35	f	0.70		1.01	80	5
Intermediate Group						
T-13-9	f					3-(4)
T-13-12	f					2
T-8-9	f					2
T-15-2	f	0.72	0.58			2
T-21-3	f	0.71		1.03	85	5
T-6-1	f	0.67		1.03	85	5
RD-57-6	f	0.71				3
T-11-2	f	0.71	0.60			4
T-6-16	f	0.73	0.68			2
T-17-6	f	0.68		1.03	85	5
T-17-7	f	0.73		1.00	78	5
T-15-32	f	0.70		0.99	76	6
T-15-19	f	0.71				3
T-15-16	f	0.70	0.58	0.98	73	3-(2)
Late Group						
T-11-6	f	0.73		0.98	73	5-6
T-11-3	f	0.70		0.97	71	6
T-14-1	f		0.49	0.90	54	3
T-14-2	f	0.68		0.99	76	4
Y-5-1	f	0.72	0.63			2
T-14-6	f	0.72	0.67	0.96	68	2-3

Table XV (contd.)

Sample Numbers	Foliated – f Massive – m	2θ Ab $02\bar{2}$ – 2θ Ab 131	2θ Ab $02\bar{2}$ – 2θ Or 131	2θ Ab $02\bar{2}$ – 2θ Mic 131	Obliquity of microcline in percent	Type of potash felspar
Late Group (contd.)						
T-17-20	f	0.71	0.69	0.91	56	4
T-14-8	f	0.72	0.56			4
T-13-00	f	0.72	–	0.99	76	4
T-13-0	f	0.73	0.64	0.95	66	4
T-13-3	f	0.72	0.61	0.99	76	4
T-13-2	f	–	–	–		4
T-13-1	f	0.74	0.62	0.99	76	4
T-13-4	f	0.72	0.61	1.05	90	4
T-21-17	f	0.77	0.60	–		2
T-18-15	f					3-4
T-18-8	f					3
T-15-5	f					3-2
Pegmatites and dykes						
Y-10-20 } Early group		0.83	0.57			1
RD-8-12 } Early group		0.83	0.53			1
RD-3-6		0.76	0.56	0.99	76	2-3
RD-4-25			0.57	0.93	61	2
RD-9-10		0.69		0.99	76	4-5
RD-5-2		0.70		0.97	71	5
RD-2-12		0.71		1.02	83	6
Phenocrysts of intermediate group						
T-15-32		0.73	0.65	1.07	95	4
T-13-11		0.62	–	–		4
T-13-9		0.71	0.60			2
T-13-12		0.75	0.67	0.88	49	2

felspar i.e. 4.

(4) Potash felspar in perthite of pegmatites that intrude the country rock and are not of local derivation corresponds to types 2-6, while that in three of the locally derived pegmatites in the early massive syenites (i.e. irregular coarse-grained phases) corresponds to types 1 and 2.

The same sequence as above was found by Parsons (1965), the youngest rock containing dominantly triclinic and the oldest dominantly monoclinic potash felspar.

The meaning of the orthoclase-microcline transformation is not clear, but has been generally believed to be related to temperature, the orthoclase being the stable high temperature phase. Wright (1967) believes that the type of potash felspar polymorph produced on cooling is related to a number of factors other than temperature, the most important of which are the bulk composition and the time the felspar was held near the temperature of transformation. Parsons (1965) favours late stage fluids as the controlling factor.

Differences in bulk composition of the felspar of the Mutton Bay intrusion is apparently unimportant as the foliated microcline-rich varieties of the early group have compositions like those of the massive varieties. The microcline-rich rocks are those with a well-developed flow foliation, suggesting a close relation between the potash felspar transformation and shearing accompanying flow in a crystal mush. There is no proof that the cooling histories of the various units were radically different. It might appear at first that the younger intrusives cooled more rapidly, having intruded at a lower temperature (see p.202) and would be less likely to have reached the stable low temperature form. However, the cooling history of the crystals in a mush begins prior to intrusion. The rate of cooling of these crystals in the foliated varieties may have been very much slower than those in the early high temperature intrusives. The apparent relation of the potash felspar transformation to shearing may be that both phenomena result from the same cooling history.

Chemical analyses of perthites

Partial chemical analyses were made for Na_2O, K_2O, and CaO on 16 samples of perthite. The analyses are listed in Table XVI and plotted in terms of weight percent felspar molecules in fig.44. Samples 3 and 4, containing quartz and carbonate respectively, were recalculated, taking into account the impurities. Fig.44 is compared with fig.45, a plot of the weight percent normative felspar calculated from the rock analyses.

The perthites fall into two distinct series. The early group of intrusives form one series in which the felspar is relatively rich in anorthite. Rare corroded oligoclase xenocrysts seen in one section of the massive green syenite indicate that the plagioclase component of the perthite probably contains the maximum amount of anorthite possible in solid solution. The curve A-B (fig.44) is believed to be the limit of solid solution between the felspars under the conditions prevalent during the crystallization of the early part of the series. This is also the limit of solid solution under conditions expected in trachytic magmas as given by Tuttle and Bowen (1958, p.132). Two rocks of the early group, poor in anorthite, plot at Or 50 percent, the composition at the cotectic

Table XVI

Chemical Analysis of Felspars

Sample	Measured Wt %			Calculated Wt %			
	CaO	Na_2O	K_2O	An	Ab	Or	Total
1	3.21	6.75	4.71	15.82	57.06	27.83	100.71
2	2.12	6.26	5.91	10.52	52.95	34.89	98.36
* 3	0.84	4.23	5.23	4.18	35.77	30.89	70.84
@ 4	4.29	5.79	6.86	21.31	48.98	40.50	110.79
5	0.90	5.82	8.17	4.47	49.17	48.27	101.91
6	0.68	5.68	8.09	3.37	47.98	47.83	99.18
7	0.25	6.73	7.45	1.26	56.84	43.98	102.08
8	0.34	6.56	6.93	1.69	55.49	40.95	98.13
9	0.34	6.72	7.16	1.51	56.79	42.33	100.63
10	0.60	6.90	6.06	2.98	58.33	35.79	97.10
11	0.37	7.19	6.39	1.83	60.82	37.79	100.44
12	0.57	6.73	7.44	2.83	56.92	43.92	103.67
13	0.48	6.76	7.28	2.38	57.12	42.99	102.49
14	0.28	7.16	6.98	1.37	60.56	41.26	103.19
15	0.46	7.19	6.64	2.28	60.78	39.22	102.28
16	0.75	7.53	5.71	3.72	63.38	33.70	100.80

* Quartz not removed from sample

@ High CaO percent due to free $CaCO_3$ not removed from sample

Analyst : R.Davies, 1966

Samples analysed

1. Coarse-grained green pyroxene syenite (A-30)
2. Coarse-grained green pyroxene syenite (R-52-7(b))
3. Pale red porphyritic quartz syenite (T-22-35)
4. Coarse-grained massive pink quartz syenite to syenite (older phase) (T-16-44)
5. Coarse-grained massive pink quartz syenite to syenite (younger phase) (T-16-39)
6. Medium- to coarse-grained green pyroxene quartz syenite (T-21-8)
7. Coarse-grained green pyroxene quartz syenite (T-31-6)
8. Medium-grained grey syenite porphyry (T-15-32)
9. Medium- to coarse-grained greenish to pinkish grey granite (T-21-3)
10. Medium- to coarse-grained well foliated grey syenite (T-15-16)
11. Medium-grained very well foliated grey syenite (T-15-19)
12. Coarse-grained greyish orange pink well foliated syenite (T-17-20)
13. Coarse-grained greyish orange pink very well foliated syenite (T-14-6)
14. Coarse-grained light grey very well foliated syenite (T-11-3)
15. Coarse-grained dark greenish grey very well foliated syenite (T-14-1)
16. Coarse-grained light grey very well foliated syenite (T-11-6)

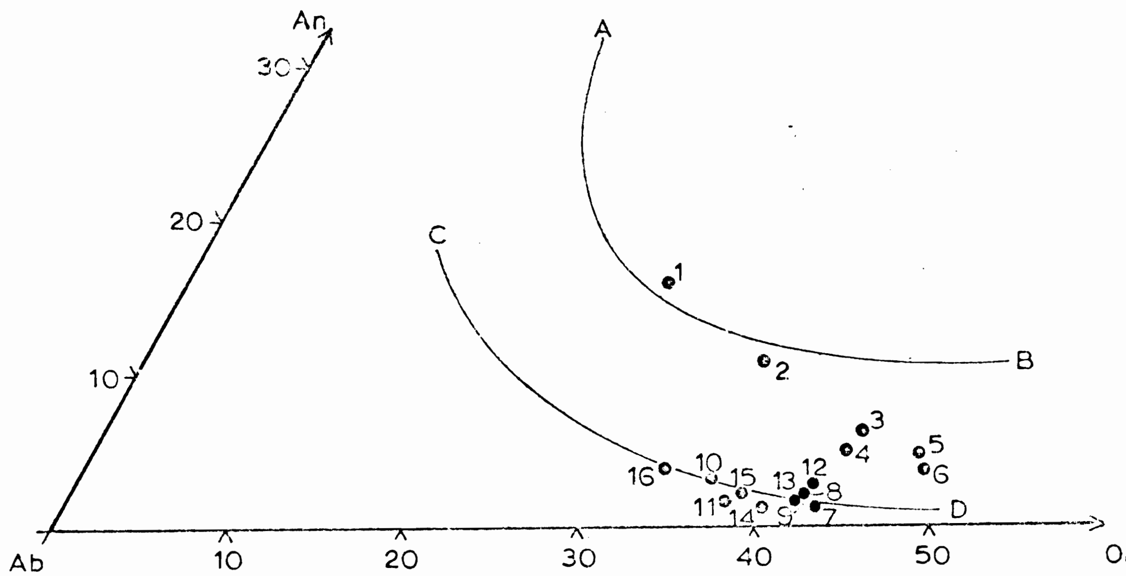


Fig. 44 - Felspars of the Mutton Bay intrusion plotted in terms of weight percent Or, Ab, and An. Sample numbers refer to Table XVI (p.131) and 1-7 belong to early group, 8-11 intermediate group, and 12-16 late group. Curve A - B is limit of solid solution for the early group and curve C - D the possible limit of solid solution for the later groups.

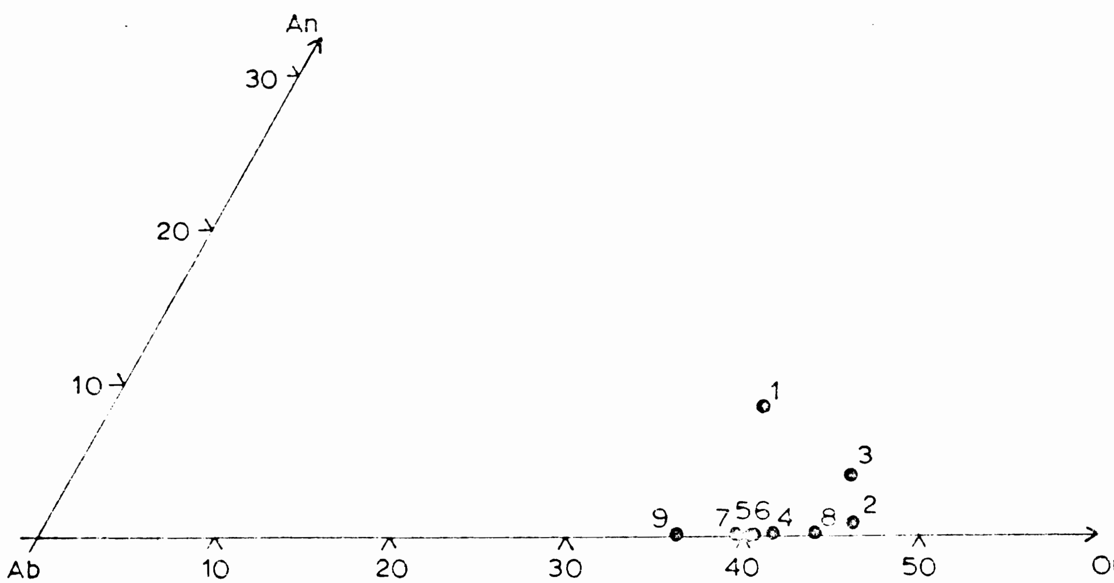


Fig. 45 - Normative felspars of the Mutton Bay intrusion plotted in terms of weight percent Or, Ab, and An. Sample numbers refer to Table XIII (p.103) and 1-3 belong to early group, 4-6 intermediate group, and 7-9 late group.

minimum of an An-poor melt at 500 bars water pressure (Winkler, 1965, p.189, after Tuttle and Bowen, 1958). It will be shown in a later section (p. 202) that most syenites of the early group crystallized from relatively dry magmas. Differentiation at depth or contamination accounts for the variation in composition of the early group.

The early massive green quartz syenite of the contact plots with the remaining rocks belonging to the intermediate and late groups around Or 40 percent, the composition of the cotectic minimum of an An-poor melt for a water pressure of 2000 bars (Winkler, 1965, p.189, after Tuttle and Bowen, 1958). The relatively high water pressure at which these syenites might have crystallized means a lower temperature of crystallization than for the early group, and the field of solid solution decreases to something close to that shown by the curve C-D (fig.44). The apparently anomalous felspar composition of the contact syenite of the early group is readily explained. The liquid component in a flowing crystal mush concentrates, together with its dissolved water, at the contacts. The dissolved water gives rise to a high water pressure during the final stages of crystallization.

Biotite

Biotite is common in most of the syenites except those of the intermediate group, and is an important mineral in the study of differentiation in the pluton. It is the last ferromagnesian mineral to crystallize, and therefore reflects the Fe/Mg ratio of the residual liquid, which itself is a reflection of the over-all Fe/Mg ratio.

Refractive indices of biotite generally increase with increasing iron content but are also affected by other substitutions. Biotites with extremely high Fe_2O_3 content have very high indices of refraction. Indices increase with Mn and Ti and decrease with F so that an optical method of determining the Fe/Mg ratio is not reliable on its own.

Measurement of the N_y index is readily made on cleavage flakes and is a rapid and convenient method of studying a large number of specimens using a minimum amount of material. In order that the variation in composition, based on the index measurements, has a firm basis, analyses were made for the major elements on eight biotites covering the range $N_y = 1.632$ to 1.714 (Table XVII). Weight percent of the oxides is plotted against N_y of the biotites in fig.46. It is evident that with increasing N_y, total iron increases and MgO, and to a lesser extent K_2O, Al_2O_3, and SiO_2 decrease. Variation in other elements is unimportant. Five biotite flakes, scanned with an electron probe, showed no significant zoning, and neither was zoning evident in thin section or during measurement of refractive indices.

The biotite of the Mutton Bay pluton is strongly pleochroic and varies from pale yellowish orange or very pale orange (X) to moderate reddish brown and dark yellowish orange ($\frac{Y+Z}{2}$). Estimates of $2V_x$ are 5–30° though most are between 5° and 15°. The refractive index N_y ranges from 1.632 to 1.729, and 77 index determinations are summarized in Table XVIII.

The table shows that biotites in the late group are richer in Fe than those of the early group, and that biotites in the younger intrusives of each group are richer in Mg than Fe.

Table XVII

Chemical analyses of biotites from the Mutton Bay intrusion

	1	2	3	4	5	6	7	8
SiO_2	33.73	37.68	36.20	36.21	38.00	39.34	37.00	36.81
Al_2O_3	14.18	12.68	11.62	14.05	13.42	13.33	12.21	12.53
Fe_2O_3	3.23	2.03	3.02	4.13	2.49	3.20	-	5.02
FeO	24.67	23.11	32.10	18.72	16.02	16.02	-	24.59
MgO	5.34	7.07	-	7.13	11.31	10.40	3.07	3.97
CaO	1.09	0.98	1.29	1.25	0.89	1.09	0.91	0.91
Na_2O	0.51	0.60	0.53	0.52	0.46	0.44	0.47	0.47
K_2O	8.13	8.31	6.96	7.94	9.12	7.88	7.66	7.99
TiO_2	4.40	3.15	2.86	4.74	2.64	3.91	3.63	3.20
P_2O_5	0.16	0.02	0.12	nil	0.05	nil	0.13	0.11
MnO	0.42	1.19	1.17	0.70	0.64	0.41	0.64	1.17
Total	95.86	96.82		95.39	95.04	96.02		96.77
R. I. N_y	1.680	1.671	1.714	1.667	1.632	1.657	1.700	1.696

Note : The amount of H_2O and F were not determined in the above analyses These two components amount to 4.10 - 7.85 percent in analyses given by Deer, Howie, and Zussmann (vol.3, 1962).

X-ray fluorescent spectrography was used to check the chemical analyses. A series of curves were obtained by plotting x-ray fluorescent intensity values against chemical analysis values for each of the oxides. Erratic errors in the chemical analyses are indicated by points that fall off the general curves. Corrections were made to the erratic values and these are underlined in the table.

Chemical analyses : J.Stevenson, 1967

X-ray fluorescent spectrography: J.Volrath, 1967

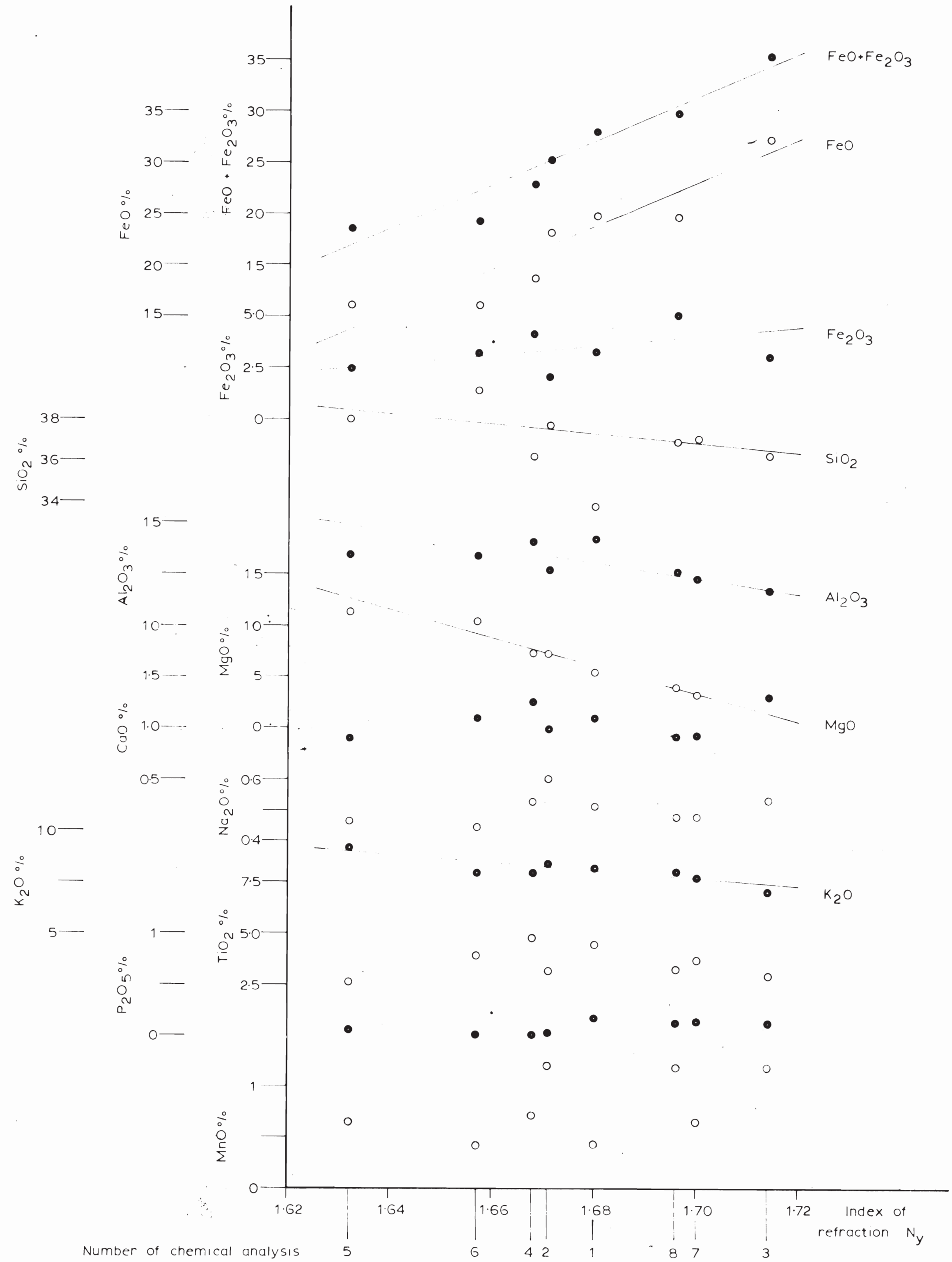


Fig. 46 - Weight percent FeO + Fe_2O_3, FeO, Fe_2O_3, SiO_2, Al_2O_3, MgO, CaO, Na_2O, K_2O, TiO_2, P_2O_5 and MnO, plotted against index of refraction N_y for biotites in rocks of the Mutton Bay Intrusion.

Fig. 46

Table XVIII

Variation in refractive index Ny of biotites from the early and late groups of the Mutton Bay intrusion

Type	Number of determinations	Range	Arithmetic Mean
Early Group			
Massive green	5	1.670 - 1.694	1.6764
Massive pink	8	1.632 - 1.676	1.6625
Massive pink-grey	4		1.6420
Late Group			
Foliated grey	5	1.694 - 1.710	1.7052
Foliated green	30	1.668 - 1.729	1.7002
Foliated pink	25	1.665 - 1.702	1.6832

Note : Index measurements were made to .001 below 1.700 and .004 above 1.700.

Five differentiated sequences in the late group were studied in detail, three in the green variety and two in the pink variety. Figs. 47 and 48 are two sequences, one above the other, separated by a block of country rock, and may be treated as a single unit. Fig.49 is a sampling of a well-differentiated sequence over only 15 inches, and a great variation in composition is not expected. Fig.50 is a sequence showing a weak gravity concentration over 50 feet and likewise no great variation in composition is expected. Fig.51 is a sequence showing mafic concentrations at both lower and upper contacts.

In all sequences studied (considering figs.47 and 48 together) there is a concentration of Mg in biotites in gravity settled mafic concentrations, but there is also a Mg enrichment in the roof concentration of late mafic minerals (fig.51), and any explanation of

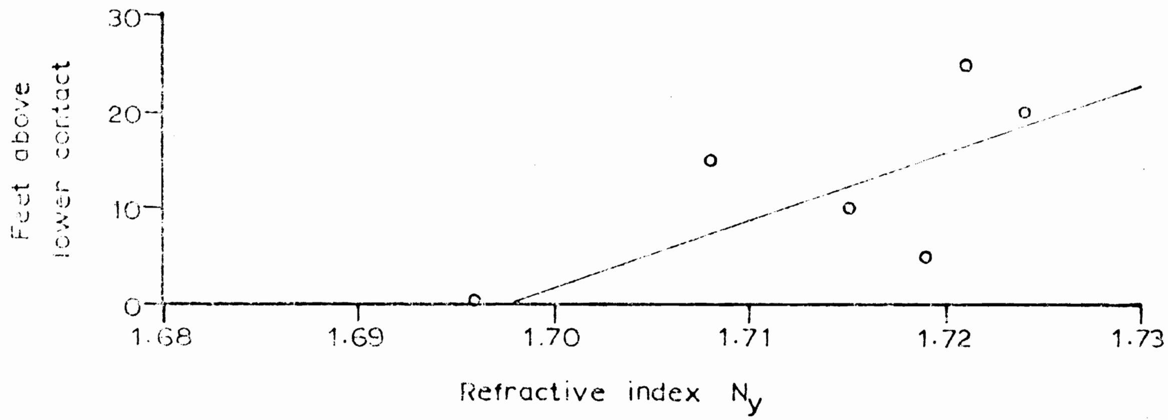


Fig. 47 - Variation in refractive index Ny of biotite across the lower part of a sequence of coarse-grained dark greenish grey very well foliated syenite dipping at 30° and with concentration of mafics at the lower contact.

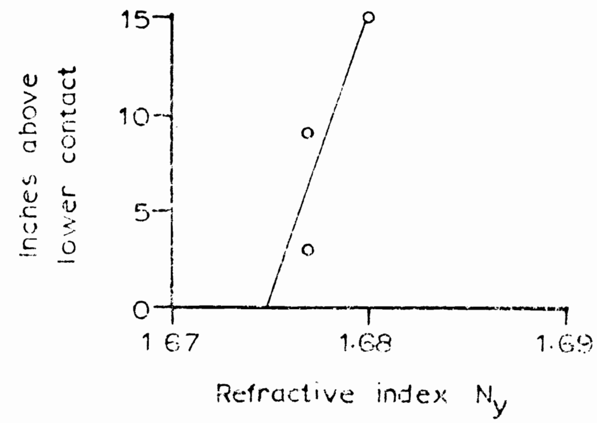


Fig. 49 - Variation in refractive index Ny of biotite across the lower part of a sequence of coarse-grained greyish orange pink very well foliated syenite dipping 30° and with a concentration of mafics at the lower contacts.

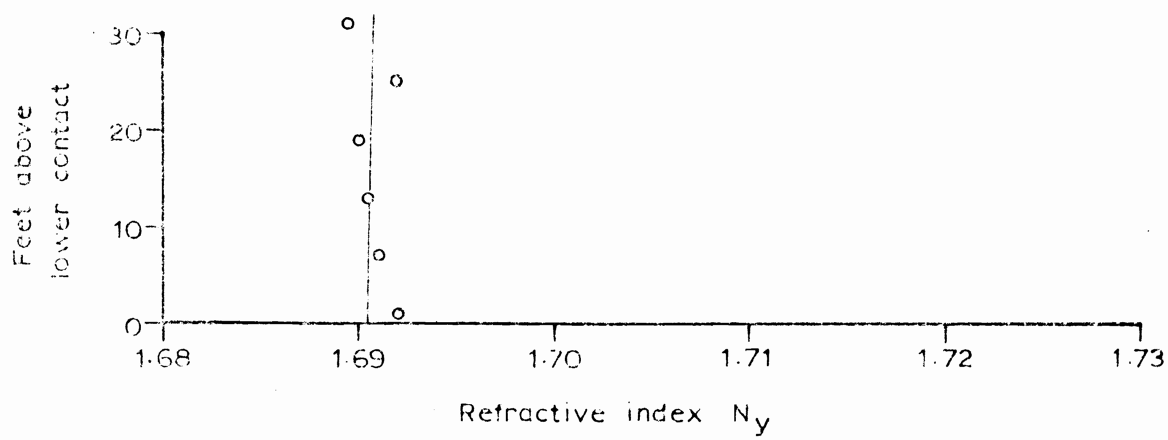


Fig. 48 - Variation in refractive index Ny of biotite across the lower part of a sequence of coarse-grained dark greenish grey very well foliated syenite dipping at 30° and lying immediately below the sequence in fig.47 but separated from it by a screen of country rock. A concentration of mafic minerals occurs at the lower contact.

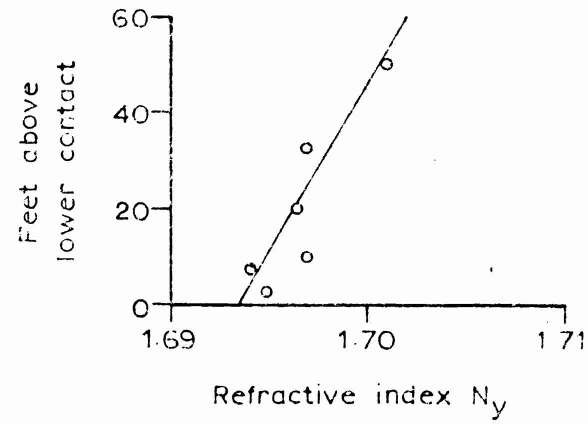


Fig. 50 - Variation in refractive index Ny of biotite across the lower part of a sequence of coarse-grained dark greenish grey very well foliated syenite dipping 60° and with a weak concentration of mafics at the lower contact.

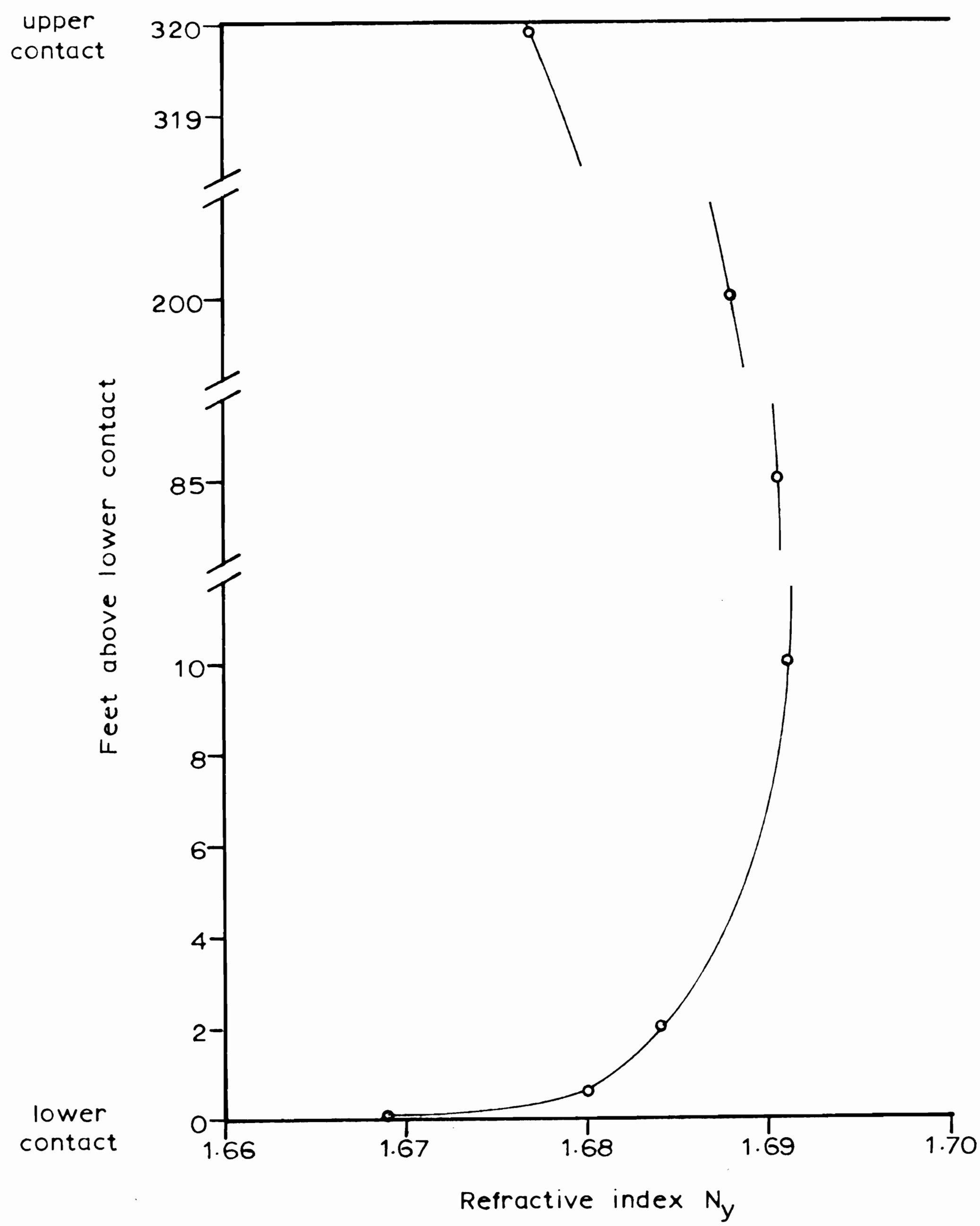


Fig. 51 - Variation in refractive index Ny of biotite across a sequence of coarse-grained greyish orange pink very well foliated syenite dipping 45°.

the Fe/Mg ratios must satisfy the latter. An irregular mafic concentration in the late very well foliated pink syenite, unrelated to any contacts, shows a variation of refractive index Ny = 1.696 $\pm$ .001 (low mafics) through Ny = 1.689 $\pm$ .001 (moderate mafics) to Ny = 1.687 $\pm$ .001 (high mafics), indicating that even in irregular mafic concentrations there is an increase in Mg with concentration of mafic minerals.

Enrichment in Fe in biotites of the late group is in accord with the chemical analyses of the rocks, which show a higher Fe/Mg ratio for the late group of rocks. Enrichment of Mg in the younger intrusives of each group can be explained by contamination with time of a Fe-rich magma by a more magnesian-rich country rock, or intrusion of successively more basic rocks, perhaps from deeper levels.

An explanation for the Mg enrichment at contacts and in mafic concentrations might be that iron oxides crystallize early in the contact zones, causing the residual liquid to be enriched in Mg. Flow would drag some of the oxides away from the contacts to the centre of the intrusion where they could melt or alter the equilibrium conditions, the net effect being to increase the Fe content at the centre of the intrusion. It was noted that mafic concentrations at the contacts in the late group have more albitic perthites, presumably caused by the concentration of late Na-rich felspathic liquid at the contacts. The high Na might cause a preferential withdrawal of Fe for the crystallization or continued growth of pyroxenes. It will be shown in a later section that the residual liquid is in fact concentrated at the contacts.

The best explanation for the variation of Fe/Mg ratios is believed to be that based on the work of Wones and Eugster (1965). It was found that the Fe/Mg ratio in biotites co-existing with sanadine and magnetite depends strongly on the water content of the magma. Since the biotite crystallizes from a residual liquid, the water content of the liquid becomes very important, and presumably increases with crystallization. Wones and Eugster found that a water-rich melt resulted in crystallization of Mg-rich biotites, while a water-poor melt results in crystallization of Fe-rich biotites. The crystallization of biotites in the Mutton Bay rocks is pictured as generally following an Fe-rich trend in relatively dry magma, but where the very last liquids crystallized, i.e. at the contacts and in the younger intrusives of each group, the water content reaches a high enough level to allow Mg-rich varieties to develop.

Amphiboles

Amphiboles are the most widespread of the ferromagnesian minerals. Invariably anhedral, and occurring interstitial to the felspar, they show wide variation in optical properties, but unlike the biotites and pyroxenes this data is not easily correlated with composition. The amphiboles belong to three series and each series characterizes one of the three main groups of intrusives.

Hornblende series

The early group of intrusives contain amphiboles whose optical properties closely correspond to the hornblende series of Tröger (1959, p.77).

$2V_x$ varies between 58° and 84°

$z \wedge C$ varies between 11° and 24°

X = dusky yellow to pale yellow and greyish orange to pale and very pale orange.

Y = pale to dark yellow brown, light olive brown, pale and greyish yellow green and greyish orange.

Z = pale olive to moderate yellow green and light to moderate olive brown.

Index of refraction Nc (index parallel to the C axis) varies between 1.662 and 1.705. The amphibole of the massive green syenite has the higher indices, indicating a high Fe content, while later intrusives of the early group have lower indices.

Intermediate group amphiboles

The intermediate group of intrusives are characterized by amphiboles with anomalous optical properties. Absorption is strong and extinction on the $x-z$ plane is difficult to determine. Using a strong light source, optical properties were measured. It was found that 9 of 11 determinations showed the mineral to be apparently triclinic with C lying on none of the optic symmetry planes. This results from the difficulty in determining extinction on the $x-z$ plane. Prismatic cleavage is 55°, eliminating the triclinic aenigmatite series which is similar in many respects to the amphiboles.

The $y-z$ plane was readily obtained and at the same time the position of x. This was plotted together with the prismatic amphibole cleavages and, assuming the mineral monoclinic, the $x-z$ plane was obtained by drawing a plane through x and C. Knowing the orientation of the $x-z$ plane, $2V_x$ could be determined as well as the pleochroic formula. $2V_x$ could be found directly in some cases with x vertical. The results obtained are by no means perfect as strong absorption and dispersion still interfere but are sufficiently accurate to be useful.

$$2V_x = 14\text{–}40^\circ \text{ (}55\text{–}60^\circ \text{ in finegrained and porphyritic units)}$$

$$z \wedge C = 10\text{–}20^\circ$$

Pleochroism is variable in browns and greens with blue rims and patches to many grains. The most common pleochroic scheme is :-

X = pale to moderate yellowish brown and greyish to dark yellowish orange

Y = moderate brown

Z = light to moderate olive and dark yellowish green

Refractive index Nc = 1.682 - 1.692.

X-ray diffraction study of these amphiboles shows a close correspondence with the riebeckite or arfvedsonite series, but the optic orientation does not fit either of the series. They show many similarities with the amphiboles of the late group. However, the blue colour around edges of grains and the anomalous optics which are probably related are very characteristic.

Barkevikite series

The barkevikite series of amphiboles characterizes the late group of intrusives. The pleochroic scheme is like that of the amphiboles of the intermediate group. The blue colour so common in the latter amphiboles is much less conspicuous and of minor importance.

$$2V_x = 30\text{–}60^\circ$$

$$z \wedge C = 10\text{–}19^\circ$$

X = very pale orange to pale yellowish brown

Y = moderate brown

Z = light brown to greyish olive

Refractive index Nc = 1.686 - 1.720. There is a reasonably good fit with the hastingsite series of Tröger (1959, p.75), which includes barkevikite.

X-ray diffraction study shows no good fit with any of the amphiboles catalogued. Barkevikite is not listed so the possibility of the amphibole being barkevikite is not ruled out.

Compositional variation

From optical data it is not possible to determine the composition of the amphiboles accurately, but it is possible in some cases to determine their composition variations.

Fig.52 is a plot of $2V_x$ of hornblendes of the early group, arranged according to age. It shows a general increase in Mg content of hornblende in younger intrusives since $2V_x$ increases with Mg content in this series (Tröger, 1959, p.77). Fig.53 is a plot of $2V_x$ of amphiboles of the intermediate group arranged according to age. Even though the composition of the amphibole is not known in this case there are two composition trends, the first trend ending with the only granite of the pluton. There is a similar break in the trend of pyroxene compositions at this point. In the barkevikites of the late group $2V_x$ increases with Mg content (Tröger, 1959, p.75). On the basis of a minimum of data, the barkevikites of the younger pink syenites appear to have a higher Fe content than those of the older green variety, but the same as those of the oldest grey variety. The Mg-rich barkevikites of the green variety are in mafic concentrations which also contain Mg-rich

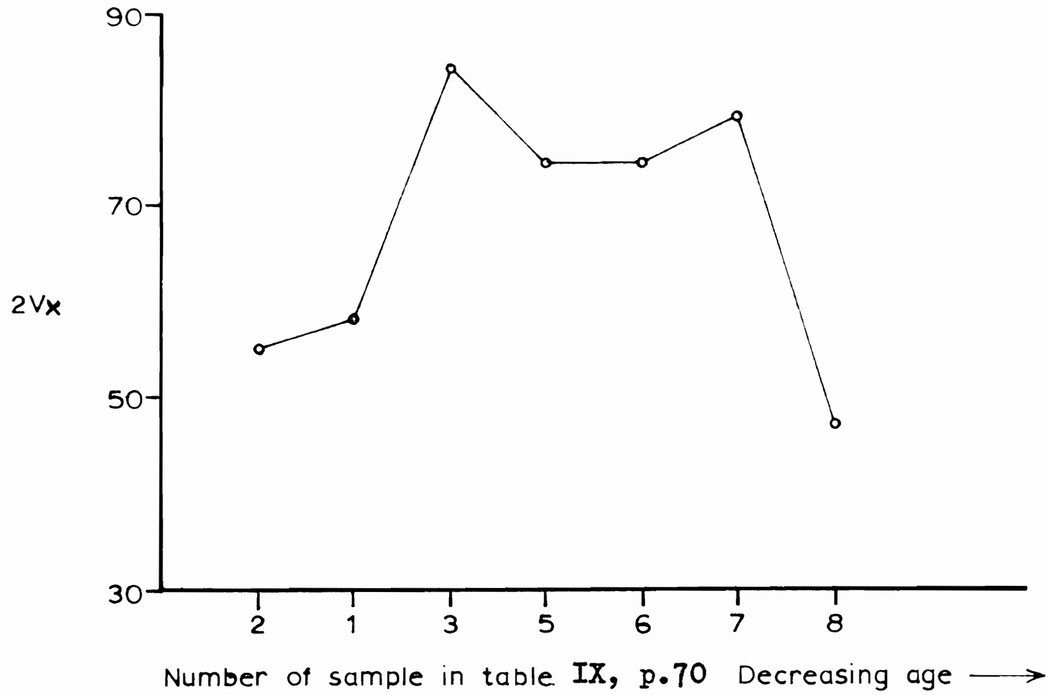


Fig. 52 - Variation in $2V_x$ of amphiboles in the early group of intrusives of the Mutton Bay pluton with respect to the relative age of the intrusive phase.

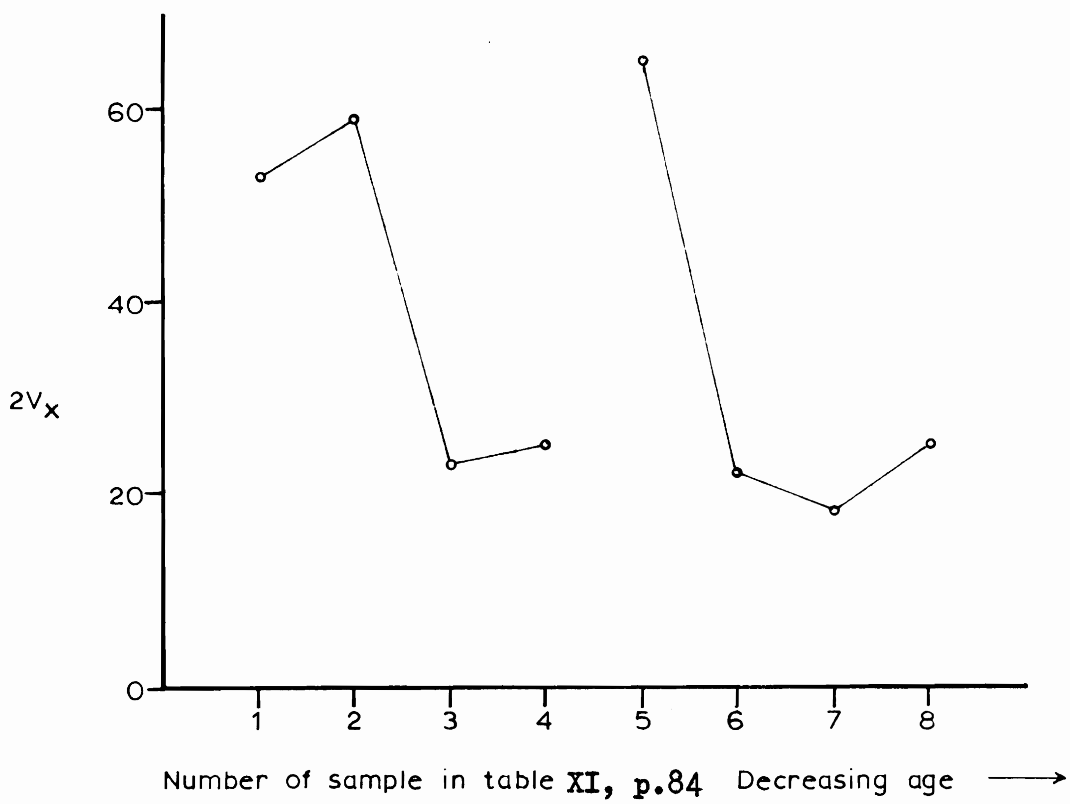


Fig. 53 - Variation in $2V_x$ of amphiboles in the intermediate group of intrusives of the Mutton Bay Pluton with respect to the relative age of the intrusive phase.

biotites. There is insufficient data to show any general trend for the group.

Amphiboles of the early group show the same variation of Fe/Mg ratio as was found in biotites in these rocks. This can be ascribed to contamination or intrusion from successively deeper levels of a differentiated igneous mass. It may also be a function of water content in the magma as was found in biotites by Wones and Eugster (1965). Biotites of the intermediate and late group show a variation in composition, but the optics of the amphiboles of the intermediate group have not yet been correlated with composition and more data is needed for the amphiboles of the late group.

Pyroxenes

Pyroxenes occur in green and grey and occasional pink varieties of syenite of all three groups, and in some rare dykes. Crystals are subhedral to euhedral and formed early (fig.54). They cover a composition range in the aegyrine-augite - aegyrine series of $(Mg_{Fe})Ca$ 100 percent to NaFe''' 86 percent (Trõger, 1959, p.64). 2V and extinction angle, plotted on Trõger's curve (1959, p.64) in fig.56, show a fairly good fit.

When $2V_z$, which varies with composition, is plotted according to the relative age of the intrusives, there is a general increase in NaFe''' in the younger intrusives, fig.57. Considering each group separately, the early group shows a small variation ($2V_z$ = 57-71°) with a higher NaFe''' content in the younger intrusives. The intermediate group has a wider range in composition ($2V_z$ = 56-80°) with two series, each increasing in NaFe''' in successively younger intrusives. The first series

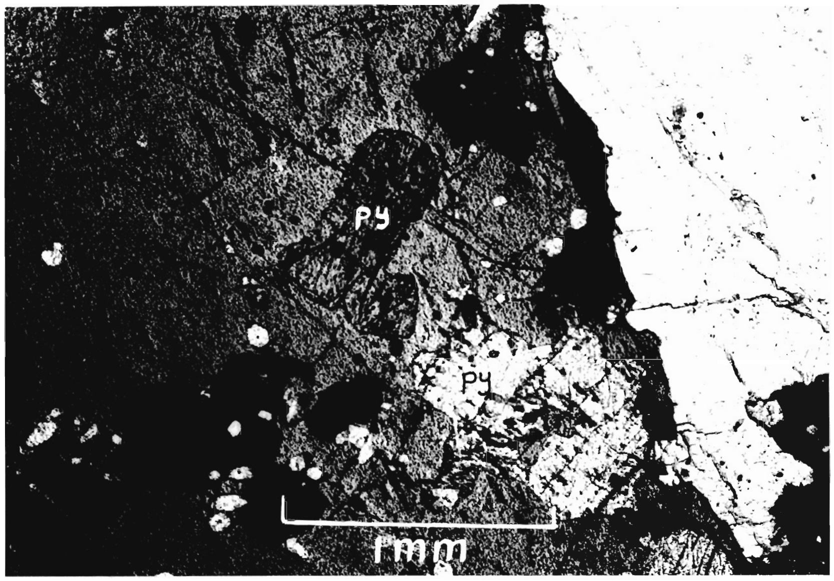


Fig. 54 - Subhedral pyroxene (py) and magnetite (black) and euhedral to subhedral apatite (small white crystals) in a large crystal of amphibole which is separated from felspar (white) by a rim of biotite in coarse-grained dark greenish grey very well foliated syenite (moderately mafic-rich variety). Plain light. X 35.

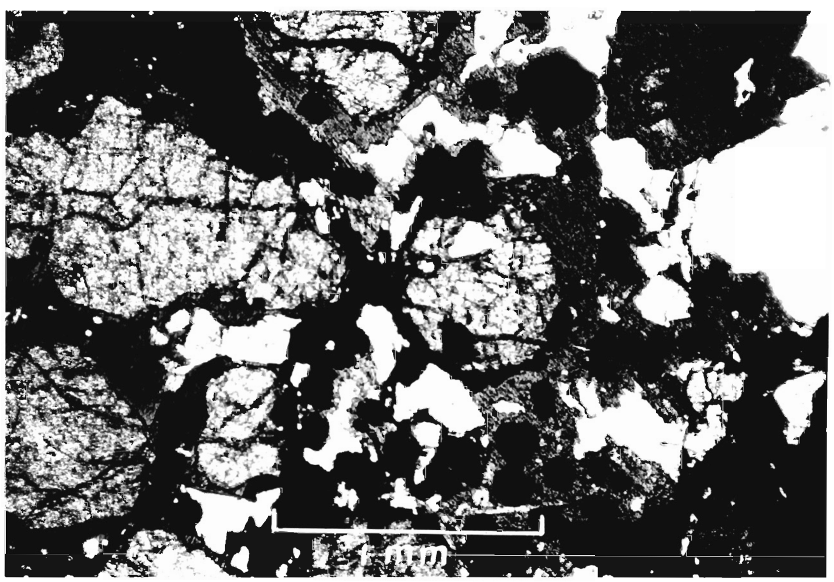


Fig. 55 - Subhedral to euhedral olivine (irregular cracks) and magnetite (black) surrounded by anhedral amphibole, biotite, and felspar (white) in a coarse-grained dark greenish grey very well foliated syenite (mafic-rich variety). Plain light. X 35.

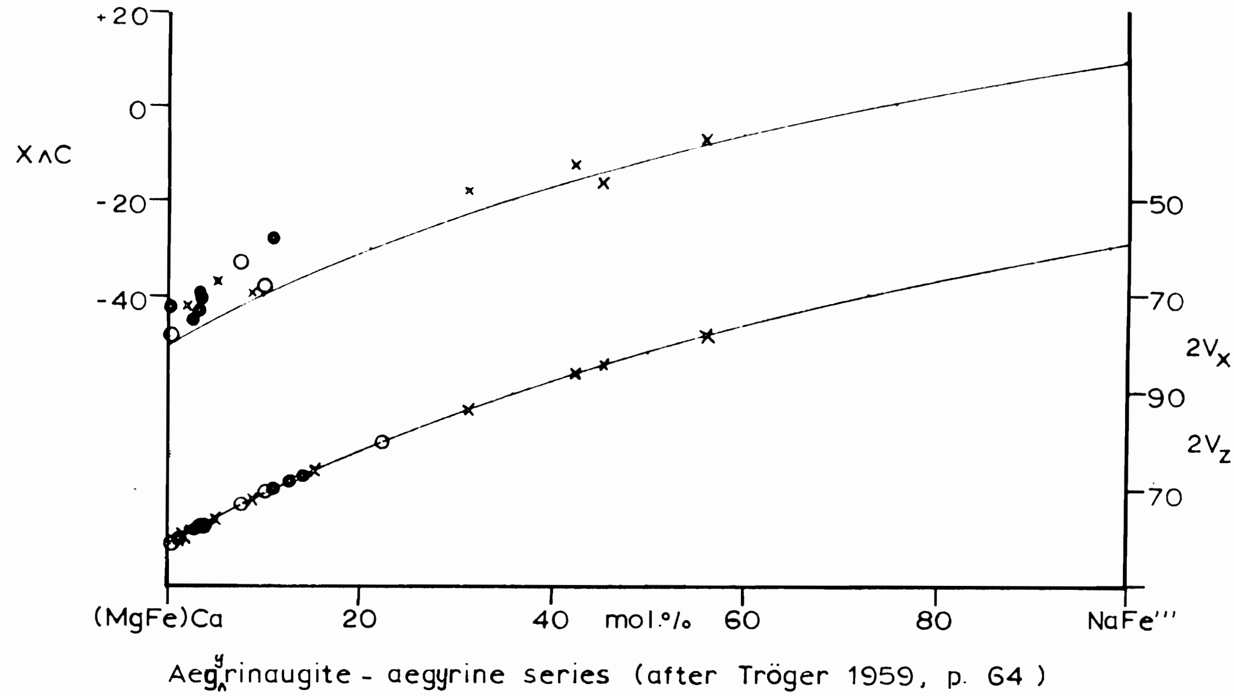


Fig. 56 - Variation in composition of pyroxenes of the Mutton Bay intrusion determined by plotting 2V on the aegyrine-augite series curve of Tröger (1959). x∧C is plotted where available. • Early group ; o Intermediate group ; x Late group.

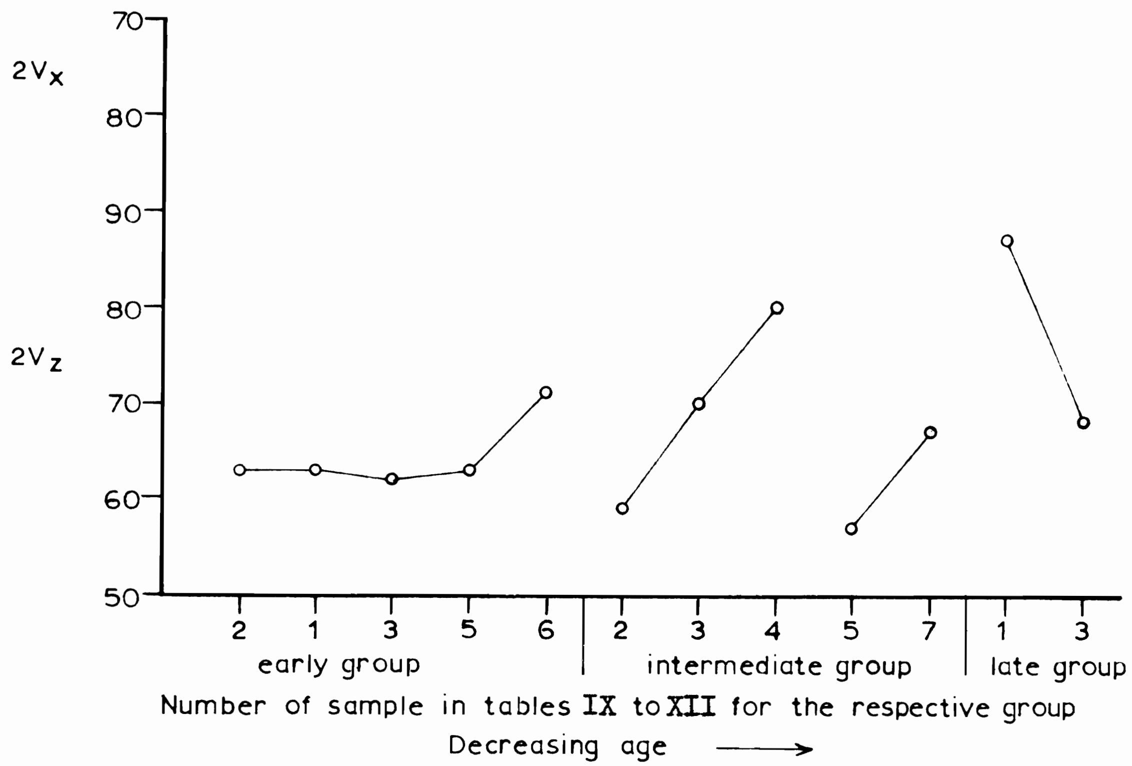


Fig. 57 - Variation in 2V of pyroxenes of the early, intermediate, and late groups of the Mutton Bay intrusion with respect to the relative age of the intrusive phase.

ends with the only granite of the pluton and has the highest NaFe''' content of the group. In the late group the NaFe''' content decreases in the younger intrusives, the $2V_z$ decreasing from a range of $85-102^\circ$ for the grey variety to $62-74^\circ$ for the green variety.

The variation in the pyroxene composition is not only between Fe and Mg but between Na and Ca. All rocks with a high NaFe''' content also have strongly albitic perthites, indicating the rocks as a whole to be more sodic than normal. It appears that the Na content rather than the Fe/Mg ratio of the rock controlled the composition of the pyroxenes.

Olivine

Olivine is a common though not abundant mineral in the green syenites of each group. It is subhedral to anhedral and crystallized early (fig.55, p.146). The colour is yellowish grey to very pale orange, and in many cases it is partially or completely altered to moderate yellow to dark yellowish brown to light olive serpentine, together with black opaques. One cleavage is generally present.

The composition range of the olivine, estimated from $2V_x$, which varies from 44° to 51°, is 95-100 percent fayalite, using the curve given by Deer, Howie, and Zussman (1962, vol.1, p.22).

Iron-Titanium Oxides

Black opaques are a common accessory in the syenites. In most cases they are subhedral and appear to have crystallized early, but in rare cases continued crystallizing at a late stage interstitial to the felspar. Magnetite is the dominant oxide and contains fine exsolved lamellae of ilmenite, oriented in three mutually perpendicular planes, and constituting no more than 20 percent of the total oxides.

Quartz

Quartz occurs in many members of the early and intermediate groups but is absent from the late group. It crystallized late, occurs interstitial to the felspar, and exhibits very little undulating extinction. In rare cases crystal faces are developed. It is concentrated in early intrusives near the contacts of the pluton where it is believed the result of contamination of the syenite magma.

Accessory Minerals

Magnetite is sometimes present in accessory amounts, but otherwise apatite is the most common accessory mineral. It crystallized early as euhedral to subhedral grains and generally appears to have preceded the magnetite. Other accessory minerals are less common and some may be restricted to certain intrusive phases. Sulphides are anhedral and include pyrite, chalcopyrite, and, rarely, molybdenite. The relative age of crystallization of the sulphides was not established. Subhedral to euhedral zircon crystallized before the magnetite. Subhedral to anhedral allanite is moderate reddish brown to greyish orange and is surrounded by pleochroic halos when enclosed in amphibole. It is sometimes zoned and has strongly pleochroic patches. Sphene occurs as anhedral to, rarely, subhedral grains or clusters of grains closely associated with magnetite, and is particularly abundant in some younger members of the early group. Carbonate is a late crystallizing accessory mineral.

Alteration Minerals

The dominant alteration product is a low birefringent, sometimes pleochroic, light olive, or dark yellowish brown, or light olive brown, or moderate yellow mineral or minerals referred to as serpentine. It generally occurs pseudomorphous after olivine and is accompanied by magnetite, but it also occurs after pyroxene. A pale green to colourless chlorite is a less common alteration product after the mafic constituents. Chlorite, carbonate, and white mica occur as alteration products of the felspar.

SATELLITIC DYKES OF THE MUTTON BAY INTRUSION

The Mutton Bay intrusion and surrounding gneiss are cut by numerous dykes. There are two distinct series, the older related to the Mutton Bay intrusion, and the younger apparently related to the giant gabbros of Ordovician age, and for which the Mutton Bay intrusion acted only as a structurally favourable host. Dykes related to the Mutton Bay intrusion are listed together with established age relations in Table XIX.

Basic lamprophyres

Basic lamprophyre dykes intruded the contact zone of the early consolidated syenite and the adjacent gneisses within a half mile of the contact. Dykes in the syenite were broken up and folded by remobilization of the host rock under pressure-temperature conditions that did not chemically alter the dykes and preserved phenocrysts and chilled contacts (fig.58). The dykes were broken up before the intrusion of the outer cone sheets.

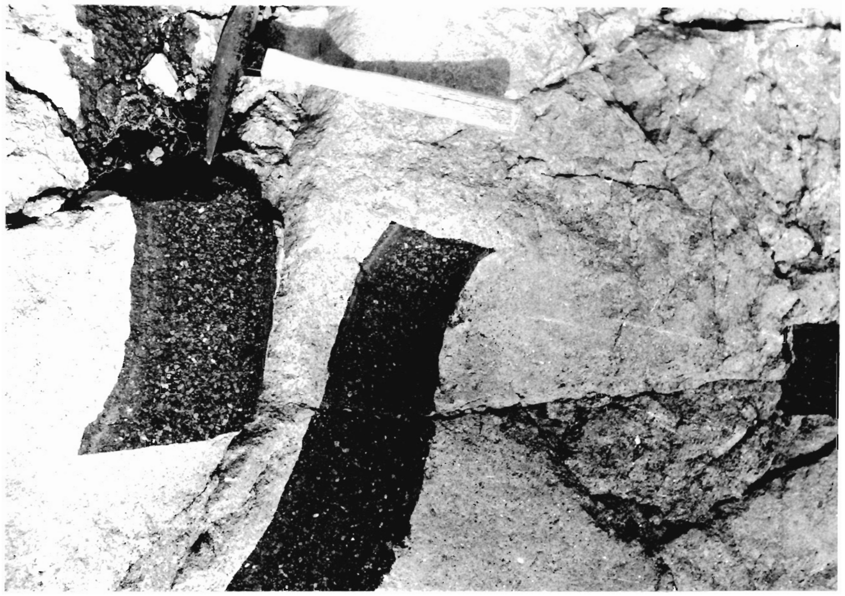


Fig. 58 - Basic lamprophyre dyke cutting medium-grained pink syenite. Note the zoning across the dyke and the chill contacts which are absent at the broken ends of the dyke fragments.

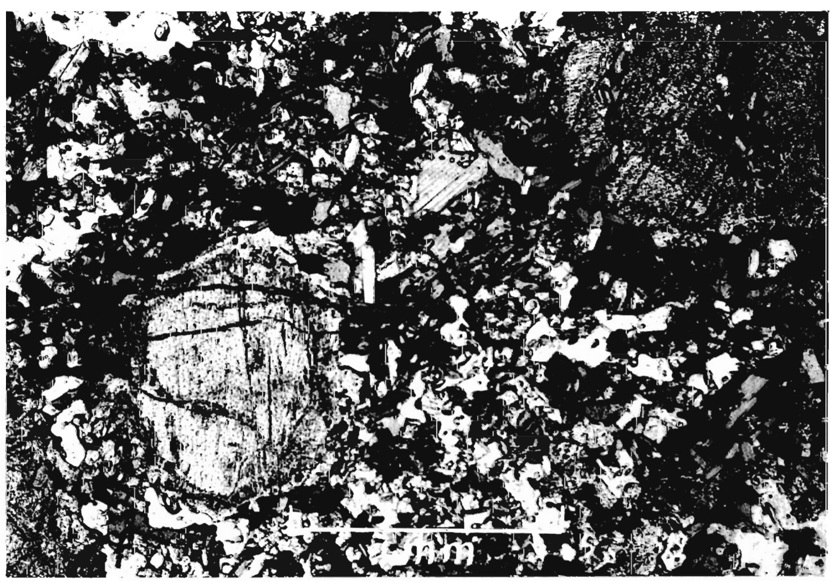
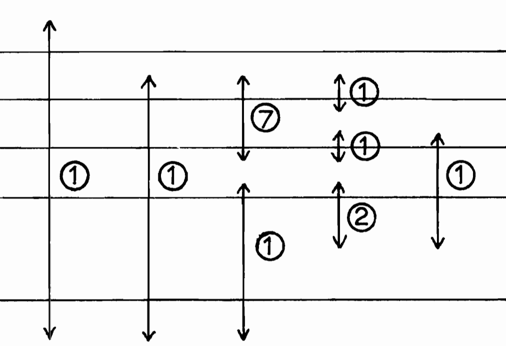


Fig. 59 - Photomicrograph of a porphyritic basic lamprophyre dyke showing a corroded augite phenocryst with a later overgrowth of inclusion-filled augite on the left, and another augite phenocryst with alteration to biotite on the right. Matrix is plagioclase - white ; biotite - flaky ; olivine, serpentine, augite - grey ; and opaques - black. Plain light. X 35.

Table XIX

Table of formations for satellitic dykes of the Mutton Bay intrusion

	Pairs of dykes between which age relations were observed and the number of times the relation was observed
Pyroxene-hydronepheline veins	
Acidic veins (quartz-bearing)	
Syenite pegmatites (cross-cutting)	
Aplites	
Syenite pegmatites (irregular and concordant)	
- ? - ? - ? - ? - ? -	
Basic lamprophyres	



Note - Dykes for which age relations were not established :
1) Amphibole veins
2) Molybdenite veins

The lamprophyre dykes are related to the syenite in time and are the most basic rocks found in the Mutton Bay syenite intrusion. The relative rarity of the dykes and their confinement to the syenite contact suggests a close genetic relation between the two rocks, and it is possible that the dykes represent a differentiate of the parent magma of the syenite. The lamprophyres may be related only to the contact of the syenite intrusion which was structurally favourable, and the basic magma could have been derived from a deeper-seated source than the syenite. The basic magma may also represent material derived from the melting of suitable country rock.

The dykes are up to 4 feet wide, medium dark grey, generally porphyritic, and are zoned parallel to the contacts. Phenocrysts of augite and olivine up to 5 mm. in diameter lie in a fine-grained groundmass. They are resistant to weathering, the augite being dark grey and shining, while pseudomorphous masses, probably after pyroxene or olivine, are greyish orange with rims more resistant than cores.

Microscopic features : A typical rock consists of a fine-grained groundmass of biotite, plagioclase, amphibole, augite, and opaque minerals, and in some cases olivine, and containing up to 25 percent phenocrysts of augite and to a lesser extent olivine (fig.59, p.151). Orthopyroxene, amphibole, biotite, carbonate, muscovite, serpentine, and opaques are alteration minerals. Sphene and zircon are accessory minerals. A modal analysis is presented in Table XX, No.1, together with the optical properties of the major minerals.

Fresh plagioclase is zoned, in one case with cores An_{42} and rims An_{25}. Olivine is anhedral to subhedral, occurring in the groundmass and as skeletal phenocrysts 1.0-3.0 mm. in diameter, its optics equivalent to a composition of $Fa_{33-35\%}$ (Kennedy, 1947). Incipient alteration to a light olive serpentine and a pale blue-green muscovite is common. Colourless augite occurs as subhedral to euhedral phenocrysts, 2-7 mm. in diameter, and as 0.2 mm. diameter anhedra in the groundmass. Inclusions are concentrated in the rims of phenocrysts, making the rims dark. The extreme rim is of a different composition, is less altered, and contains the largest inclusions. Orthopyroxene is a hypersthene - ferrohypersthene (Tröger, 1959, p.59), and occurs as pseudomorphous masses after clinopyroxene together with a colourless to pale olive amphibole,

Table XX

Modal analyses and optical properties - satellitic dykes of the Mutton Bay intrusion

	1	2	3
Quartz	-	11.9	-
Plagioclase	9.7	-	-
Microperthite	-	83.6	86.9
Olivine	4.7 (½ as phenocrysts)	-	-
Pyroxene	40.9 (½ as phenocrysts)	-	3.8
Amphibole	5.1	2.5	2.4
Biotite	30.9	0.2	-
Opaques	2.5	1.2	4.5
Apatite	-	0.2	-
Carbonate	-	0.2	-
Sphene	-	0.2	-
Alteration minerals	6.2	-	2.4

Pyroxene	I	II
2Vz	57°	123°
z∧C	34°	0°
X	-	-
Y	-	-
Z	-	-

Amphibole	I	II	III	
2Vx	78°	88°	84°	64°
z∧C	13°	22°	14°	18°
X	cl.	cl.	cl.	gyh.y
Y	l.b	to	p.ol	ol.gy
Z	m.b	l.gn	-	gyh.gn

Plagioclase		
%An	42 (max.)	5-10
Potash felspar		
2Vx	-	54°
Biotite		
Ny		-
Olivine		
2Vx	81°	-

Symbols for pleochroic colours : cl - colourless ; l - light ; p - pale ; m - moderate ; b - brown ; gn - green ; ol - olive ; y - yellow ; gy - grey ; gyh - greyish.

Samples

1. Porphyritic basic dyke (R-26-27)
2. Fine- to medium-grained pale red aplite dyke (R-47-17)
3. Fine- to medium-grained olive grey aplite dyke (RD-11-16)

Modal analyses on single thin sections counting 500-1000 points biotite, muscovite, and opaque minerals. A colourless to moderate brown amphibole with pleochroic colours similar to that of biotite occurs as anhedral grains in the groundmass, and as incipient alteration after pyroxene phenocrysts. A third colourless to greenish amphibole is an alteration product found with carbonate and biotite.

Aplites

Aplite dykes are confined to, and are abundant in the syenite pluton. Their attitude is more variable than that of the younger series of dykes and they commonly have shallow dips (fig. 135, p.275) having filled tension joints related to the geometry of the cooling pluton. The younger dykes filled vertical joints opened at a later date by regional forces. The aplites are not spectacularly weathered by wave action as are the younger dykes.

The aplite dykes are fine- to medium-grained, are very felspathic, and may contain considerable amounts of quartz. They are often observed cutting each other but care should be exercised in establishing age relations as one aplite dyke was observed apparently cutting itself. This is possible when part of the dyke solidifies and another remains mobile. Some dykes are clearly older than others and, like the basic lamprophyres, have been deformed by remobilization of the host rock.

It is probable that the aplites represent the residual melts of the various phases of syenite, and the composition might vary according to the related syenite phase.

Microscopic features : A typical pale red variety consists essentially of microperthite and quartz with lesser amounts of magnetite, amphibole, sphene, biotite, and carbonate, with accessory amounts of zircon and apatite. Green chlorite is an alteration product. An olive grey variety contains pyroxene but no quartz. Modal analyses and optical properties of minerals are given in Table XX, Nos.2 and 3 (p.154).

Magnetite crystallized early and occurs as small anhedral to subhedral crystals enclosing subhedral to euhedral apatite and, together with euhedral zircon, is in some cases enclosed by anhedral sphene. Pyroxene found in the olive grey variety is sodic with pleochroism from dusky yellow to moderate yellowish green. Green amphibole is anhedral and encloses the above early minerals. Biotite crystallized late as small anhedral flakes closely associated with carbonate. Both occur with the other mafics and as small grains in the felspar.

Microperthite occurs as subhedral to anhedral laths exhibiting simple twinning both as 5 mm. long phenocrysts and $\frac{1}{2}$-1 mm. long crystals in the fine-grained matrix (fig.60). The potash felspar component of the perthite has $2V_x = 54^{\circ}$ and the plagioclase is albite (An_{5-10}). The degree of un-mixing is greatest around the borders of grains.

Quartz occurs as small (0.1 mm. in diameter) equigranular crystals interstitial to the felspar, but is concentrated at the contacts where, except right on the contact, it occurs as larger grains (0.25 mm. in diameter) than in the centre of the dyke (fig.61). It crystallized last and was concentrated at the contacts by differential flow.

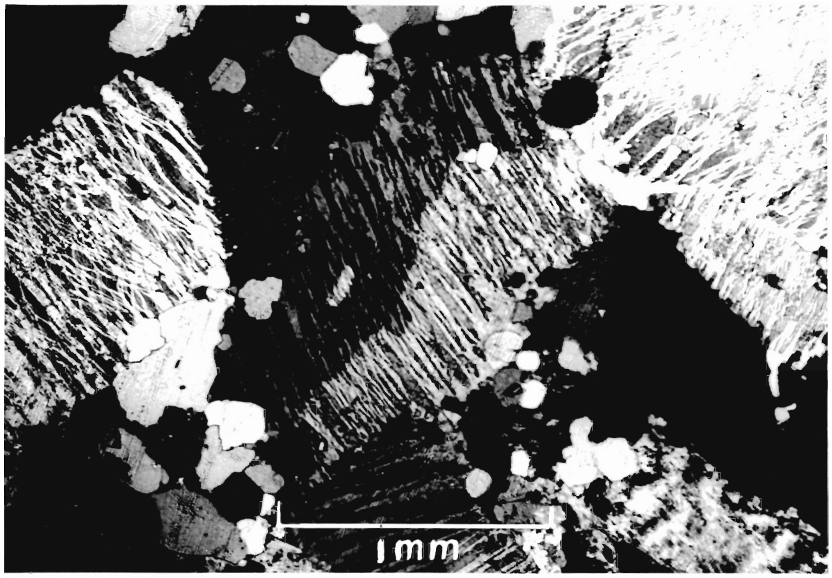


Fig. 60 - Photomicrograph of a fine- to medium-grained aplite dyke showing twinned microperthite and small interstitial quartz grains. Crossed nicols. X 35.

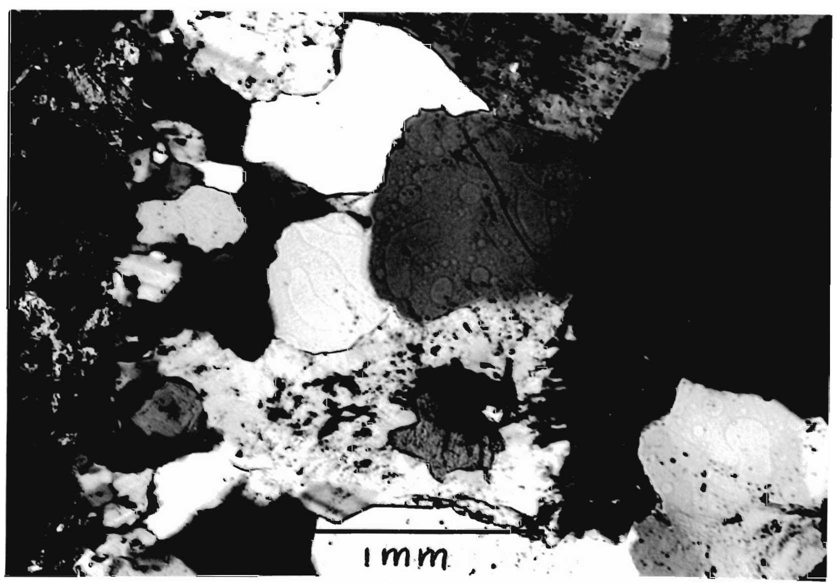


Fig. 61 - Photomicrograph showing a concentration of quartz at the contact (left) of an aplite dyke. Small quartz grains at the contact are followed away from the contact (right) by large grains, while quartz further towards the centre of the dyke is an intermediate size. Crossed nicols. X 35.

Syenite pegmatites

Pegmatitic phases are common in many of the syenite units and occur as irregular masses, concordant layers, and cross-cutting dykes. They usually have the same colour and mineralogy as the country rock and appear to have crystallized from magma that for some reason achieved a coarse grain size. Felspar crystals up to 6 feet in length were seen in a pegmatite mass in light brownish grey well foliated syenite at Mutton Bay Point (fig.62).

Irregular pegmatites : Irregular pegmatites are in no way intrusive into the host rock. They represent either slow growing early crystals or late crystals that grew in pockets of magma after flow of the magma had ceased. These pockets might have had a high volatile content, though enrichment of volatile elements was not observed in these pegmatites. Evidence of early crystallization is found in the coarse-grained very well foliated green syenite where large crystals are sometimes found scattered throughout the rock (fig.63).

Concordant pegmatites : In the light brownish grey well foliated syenite at Mutton Bay Point concordant pegmatites are very common (fig.64). The finer, well foliated host rock appears to be the younger rock in this case.

Intrusive pegmatites : Many pegmatites are intrusive, even though they are apparently related to the country rock. One such discordant pegmatite at Mutton Bay Point contains felspar crystals oriented parallel to those in the country rock, which suggests either that the pegmatite crystallized during flow of the country

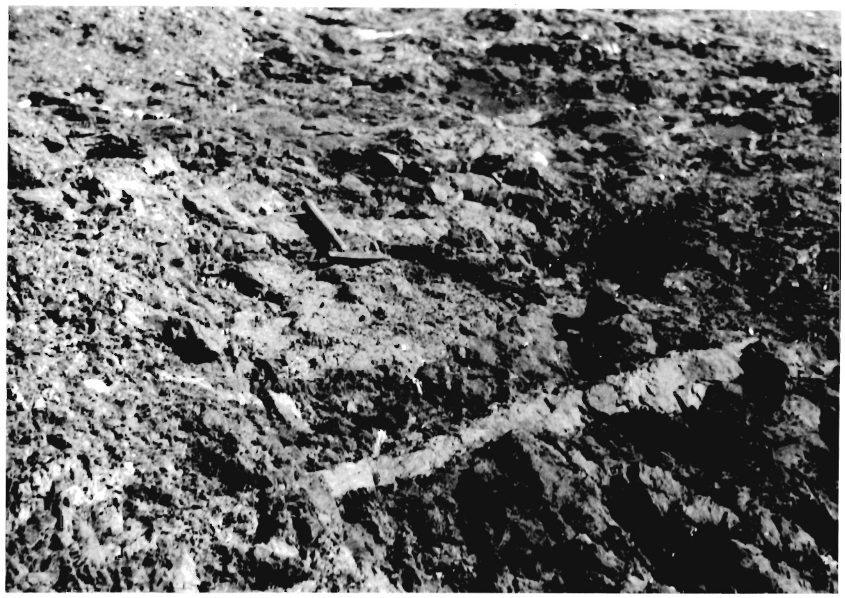


Fig. 62 - Pegmatite with felspar crystals up to 6 feet long in light brownish grey well foliated syenite. Mutton Bay Point.

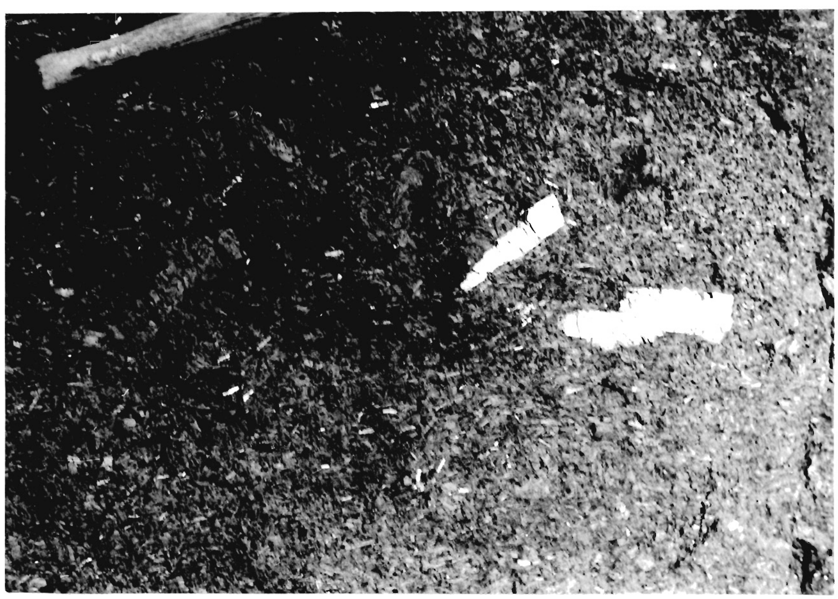


Fig. 63 - Large felspar phenocrysts in coarse-grained very well foliated green syenite. White crystals are those reflecting light from cleavages. Lac Salé.

Fig. 64 - Concordant pegmatites in light brownish grey well foliated syenite at Mutton Bay Point.

Fig. 65 - Gravity settling of dark minerals at the lower contact of a pegmatite cutting coarse-grained well foliated pink syenite. Lac Salé.

rock magma, or that crystals in the country rock acted as nuclei during crystallization of the pegmatite magma. Another pegmatite in coarse-grained foliated pink syenite at Lac Salé exhibits gravity settling of heavy minerals (fig.65, p.160), which shows clearly that the pegmatite crystallized from magma intruded after consolidation of the country rock.

Acidic veins

Throughout the syenite mass are small quartz-rich veins believed to represent the residual liquid of one or more of the quartz-bearing phases of the Mutton Bay syenite.

Hypersthene - microcline - quartz veins : Many of these veins are zoned with crystal growth perpendicular to the walls. In one horizontal dyke gravity settling of the mafics was observed (fig.66).

Mineralogically the dykes are composed of albite, microcline, quartz, orthopyroxene, and amphibole, with lesser amounts of opaques, carbonate, serpentine, allanite, and zircon.

Pyroxene occurs as large euhedral to subhedral crystals with medium-grained quartz and microcline in a fine-grained groundmass of albite and microcline. The pyroxene is twinned and zoned with strong pleochroism from pale yellowish green to yellowish grey. It is ferrohypersthene-eulite, and has $2V_x = 62\text{-}65^\circ$ and $N_z = 1.762 \pm 0.002$. In some cases amphibole occurs as a rim around the pyroxene, the two minerals having a common C-axis. It has a similar pleochroic scheme and colour but its cleavage sets it apart. It is poikilitic and contains quartz, carbonate, and moderate yellow serpentine inclusions.

The first of the two felspars to crystallize was microcline.

Fig. 66 - Growth of mafic crystals perpendicular to contacts and settling of mafic minerals in the lower contact of a hypersthene-microcline-quartz vein cutting coarse-grained massive pink syenite. Baie-de-la-Terre.

Fig. 67 - Aegyrine-hydronepheline vein with aegyrine growing perpendicular to the contacts. The vein cuts a basic lamprophyre dyke which is also intruded by coarse-grained syenite pegmatite. Mutton Bay Point.

It exhibits typical twinning and occurs as anhedral phenocryst-like grains.

Fine anhedral black opaque minerals occur in minor quantities. Euhedral to subhedral zircon and subhedral allanite are common accessories.

Aegyrine-augite - black opaques - quartz veins : These veins are small, generally 1-2 inches wide. Quartz is abundant and black opaque minerals are the main mafic constituent. Pyroxene occurs as large poikilitic grains and is an aegyrine-augite with $2V_z = 86^o$ and $z \wedge C = 22^o$, X = moderate green ; Y = dark yellowish green ; Z = dusky yellow. Other minerals present are perthite, greyish and moderate green amphibole, apatite, and sphene.

Pyroxene - hydronepheline veins

Two pyroxene - hydronepheline veins were observed cutting the syenite pluton. They consist essentially of aegyrine to aegyrine-augite with albite and hydronepheline. Fluorite, opaque minerals, sphene, muscovite, and carbonate are accessory minerals. The pyroxene grows perpendicular to the dyke contacts (fig.67, p.162) and its grain size and the thickness of crystals increases towards the centre of the dyke. In one dyke it is aegyrine with $2V_x = 64^o$ and $x \wedge C = 0\text{-}4^o$, and in the other is aegyrine-augite with $2V_x = 80\text{-}82^o$ and $x \wedge C = 12^o$.

Plagioclase is relatively fresh and is white in hand specimen. The hydronepheline is waxy with a red colour in hand specimen, and in thin section is finely micaceous with flakes having a constant orientation in each grain. The vein with the less sodic pyroxene contains less hydronepheline and in addition contains muscovite and carbonate. Fluorite is concentrated in its core.

The above veins represent the most sodic rocks in the area and the only ones containing felspathoids. A reasonable assumption is that the veins represent the end phase of one of the Mutton Bay syenite units. They were observed only in the syenite mass and crystallized slowly with little movement in the magma.

Amphibole veins

Amphibole veins, generally less than ½ inch wide, are found along joints and fractures in and near rocks of the intermediate group. The amphibole is a dark grey to dusky blue in hand specimen, and many veins have a pronounced lineation parallel to the contacts. Microscopically the amphibole is similar to that found in the intermediate group which belongs to the 'riebeckite' series. Pleochroism is in light olive grey, dark yellowish green, and yellowish grey. The veins are believed to be a late residual mafic liquid of one or more members of the intermediate group.

Molybdenite veins

Molybdenite occurs in rosettes up to 4 cm. in diameter and 1 cm. thick along narrow riebeckite veins (1-10 mm. thick) in a miarolitic zone cutting syenite. Cavities filled with clear quartz and/or calcite (dogtooth spar) occur along the riebeckite veins, and a minor amount a chalcopyrite occurs alone or with the molybdenite. Also associated with the riebeckite veins are fine-grained pale red aplite veins (½-1 inch wide) containing disseminated flakes of molybdenite. The aplites are composed essentially of anhedral equidimensional grains of perthite (0.2 mm. in diameter) with small amounts of amphibole, opaque minerals, chlorite and sphene.

The rock cut by the riebeckite veins is strongly enriched in late-stage minerals. Quartz, albite, and carbonate occur interstitial to the original minerals and the normal green to brown amphibole is strongly altered to a blue variety of the riebeckite series. Biotite in some cases is altered around the rims to a biotite with reversed absorption colours.

Normal $\frac{Z + Y}{2}$ = moderate brown X = dark yellowish orange

Altered $\frac{Z + Y}{2}$ = dark yellowish orange X = light brown

The altered biotite in turn is rimmed by blue amphibole which suggests that the altered biotite is Na-rich. Similar biotites are found at Oka (Gold, personal communication).

DIFFERENTIATION AND CONDITIONS WITHIN THE MAGMA CHAMBERS OF THE PLUTONIC ROCKS

Syenite - Gneiss Contacts

Very little of the syenite-gneiss contact is exposed, mainly because of differential weathering of the two rocks. The contact lies at the foot of steep slopes and is generally covered by reworked glacial material which supports a dense vegetation cover (fig.68).

On the south side of the entrance to Anse Bastien the contact is exposed on the shore near water level for about 15 feet. It is well-defined on a smooth, rounded outcrop, and consists of a narrow reaction zone 1-2 feet wide (fig.69) separating early coarse-grained green pyroxene quartz syenite from unaltered gneiss. The reaction zone exhibits a weak foliation that does not coincide with either

Fig. 68 - Syenite-gneiss contact, Anse Bastien. Contact follows the line of trees but is exposed for a short distance at the shore.

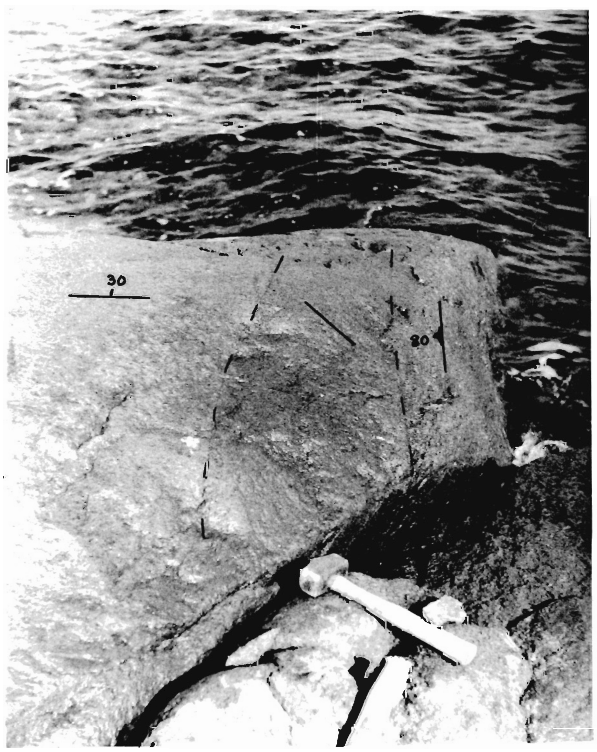


Fig. 69 - Contact as above. Coarse-grained green pyroxene quartz syenite (right) separated from green pyroxene plagioclase gneiss (left) by an 18-inch wide mixed zone. Contacts and approximate foliation in the three zones marked in ink.

the flow foliation of the syenite or the gneissosity of the gneiss, and is ascribed to dragging of the gneissosity once the gneiss was sufficiently melted or mixed with syenitic material to flow. The dip of the foliation in the contact zone was not determined but the change of strike indicates dragging by a downward flow of magma.

Thin sections show the reaction zone to be a mixture of syenite and gneiss. Corroded oligoclase rimmed by albite which grades into microperthite is surrounded by grains of microperthite, quartz, and altered ferromagnesian minerals. Chlorite with opaque minerals, sphene, and minor serpentine are alteration products after amphibole and pyroxene, and decrease in amount towards the syenite. Biotite is present in minor amounts, and apatite, sphene, and zircon are accessory minerals. Oligoclase is the only mineral of the gneisses to survive unaltered.

Xenoliths of altered green pyroxene-plagioclase gneiss are exposed in the coarse-grained green and pink quartz-syenite at Anse Bastien and on islands east of Île Fecteau. Most grade into and are being absorbed by the syenite. Xenoliths of pink granitic gneiss are lacking in the same rocks, suggesting that they were completely absorbed by the syenite, whereas xenoliths of amphibolite are fairly common and are relatively unaffected. The largest xenolith observed measures 30 x 50 feet. A xenolith of green pyroxene-plagioclase gneiss in pink syenite shows spinel, cordierite, and chlorite or muscovite growing at the expense of microcline and biotite. The xenolith has good foliation (fig.70) but much of the felspar is like that of the syenite and appears to have grown in place. Unaltered pyroxene of the gneiss is a

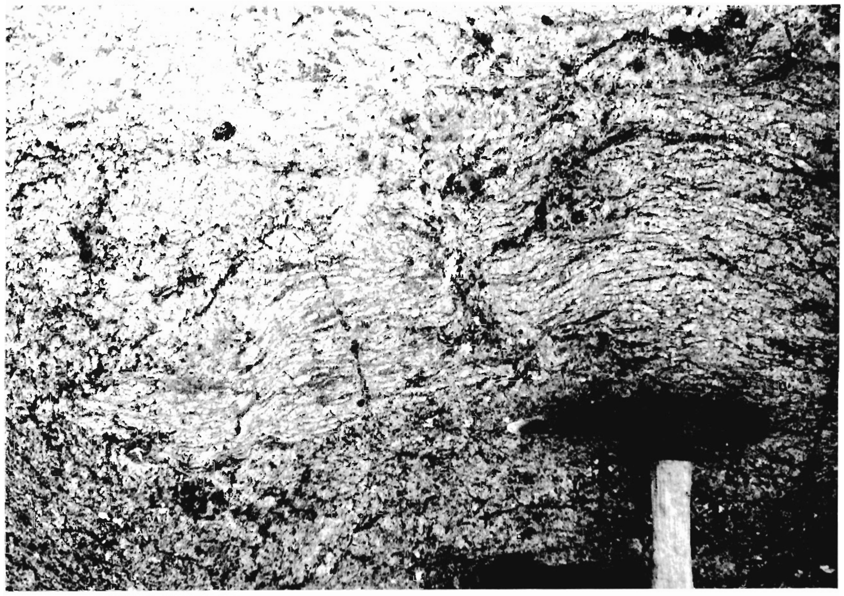


Fig. 70 - Coarse-grained massive pink syenite assimilating an inclusion of pyroxene plagioclase gneiss (good foliation). Islands east of Île Fecteau.

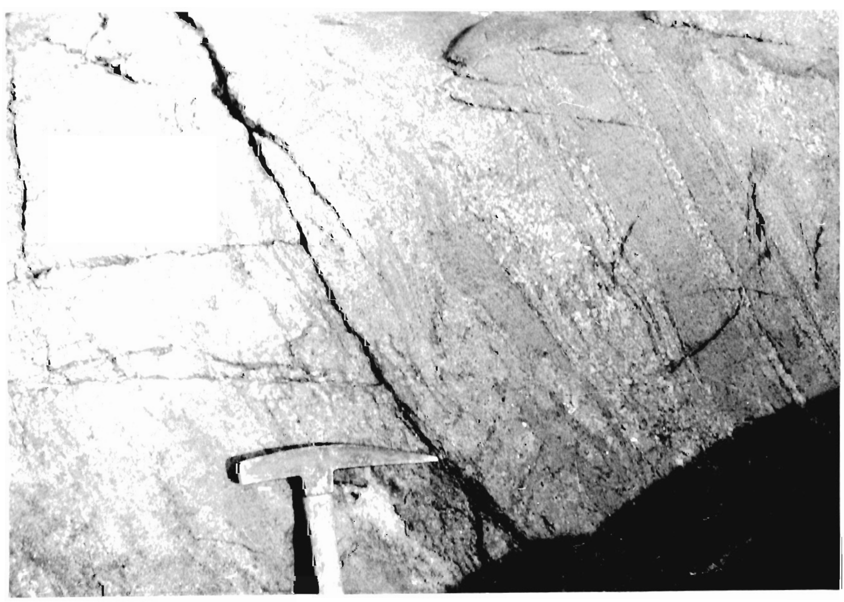


Fig. 71 - Medium-grained granitic gneiss (dark) being intruded and assimilated parallel to its foliation by medium-grained massive pink quartz syenite (light). West of Mutton Bay.

pleochroic hypersthene, $2V_x = 67^\circ$.

The contact is exposed at several places near Mutton Bay but the best exposure is on the south side of the small bay southwest across the neck from Baie du Portage. About 130 feet of coarse-grained massive pink quartz-syenite is exposed adjacent to medium-grained granitic gneiss, but separated by about 15 feet of medium-grained massive pink quartz syenite to granite. On the one side the medium-grained quartz syenite to granite injects the gneiss parallel to the layering and appears to assimilate it (fig.71, p. 168), and on the other side grades into the coarse-grained quartz-syenite which first appears in it as patches. The contact is well-exposed again a mile southeast of the above locality on the south side of the prominant point. Here coarse-grained pink quartz-syenite is seen cutting green gneiss. About a half mile further southeast coarse-grained pink quartz-syenite passes into coarse-grained pink granite. The contact is irregular and fairly sharp but difficult to see as the two rocks are very similar in appearance. They differ essentially in quartz content and the felspar of the syenite is more grey than that of the granite. Continuing to the southeast the contact follows the shoreline and the country rock becomes a medium-grained pink granite gneiss.

Contacts exposed on Lac du Gros-Mécatina are generally poor because of algae covering the lakeshore outcrops. Pink syenite cuts amphibolite at the north end of the lake, and on the large island in the lake pink quartz-syenite intrudes green pyroxene-plagioclase gneiss. Opposite the mouth of rivière du Gros-Mécatina coarse-grained pink syenite and quartz-syenite cuts green pyroxene-plagioclase gneiss in several places.

Xenoliths, Xenocrysts, and Phenocrysts

Xenoliths, xenocrysts, and phenocrysts are common in the Mutton Bay intrusion. Xenoliths pose no problem in the field but whether a crystal is a phenocryst or a xenocryst is in most cases difficult, if not impossible, to decide. The definitions of the three terms used are as follows :

Xenolith - Allothogenous rock fragments that are foreign to the body of igneous rock in which they occur, an inclusion. Tyrrell (1956) defines cognate xenoliths as those representing fragments of rocks which are genetically related to the enclosing rock and which in most cases have been formed at an early stage of crystallization. He defines accidental xenoliths as those which have been fortuitously included within the igneous rock as a consequence of its intrusion or extrusion.

Xenocryst - Allothigenous crystals in igneous rocks that are foreign to the body of rock in which they occur.

Phenocryst - One of the relatively large and ordinarily conspicuous crystals of the earliest generation in a porphyritic igneous rock.

Xenoliths

a) Accidental xenoliths : Accidental xenoliths are easily recognized as belonging to earlier intrusive phases of the syenite or to the gneissic terrain the syenite cuts. The majority are angular, but those mineralogically similar to the host rock may be rounded by partial melting. Granitic xenoliths are conspicuously lacking as they are readily digested by the syenite (fig.70, p.168).

Basic material is the most resistant to melting. There is a tendency for green syenites to become red when occurring as inclusions.

b) Cognate xenoliths : Cognate xenoliths are common in the rocks that form the outer cone sheets of the early group. They also occur in the first members of the intermediate group which form the first inner cone sheets.

The xenoliths are generally dark and conspicuous in the field (figs.72 and 73). They are fine-grained, or porphyritic with a fine-grained matrix, and invariably show good flow foliation. The xenoliths are elongated parallel to their own foliation and are oriented parallel and subparallel to the foliation of the host rock. Their rounded form is believed due to the plucking off of the crystals along edges during flow. It is possible that some xenoliths may be smeared out parallel to the flow direction by partial melting and re-orienting of the crystals. There is evidence that some xenoliths have fractured perpendicular to the flow layers and the blocks have been pulled apart in the direction of flow as in boudinage formation.

Xenoliths are widely disseminated in the foliated sphene-bearing syenites of the early group and the same material that constitutes the xenoliths is found in place at one of the contacts of these intrusives. Subrounded xenoliths are found in the contact zone of the medium- to coarse-grained green pyroxene quartz syenite where it cuts coarse-grained massive pink syenite. Cognate xenoliths common in the first members of the intermediate group may in some cases be so numerous that the rock is better described as

Fig. 72 - Dark grey rounded medium-grained cognate xenoliths in medium- to coarse-grained well foliated slightly porphyritic pale red syenite of the sphene-bearing sub-group of the early group.

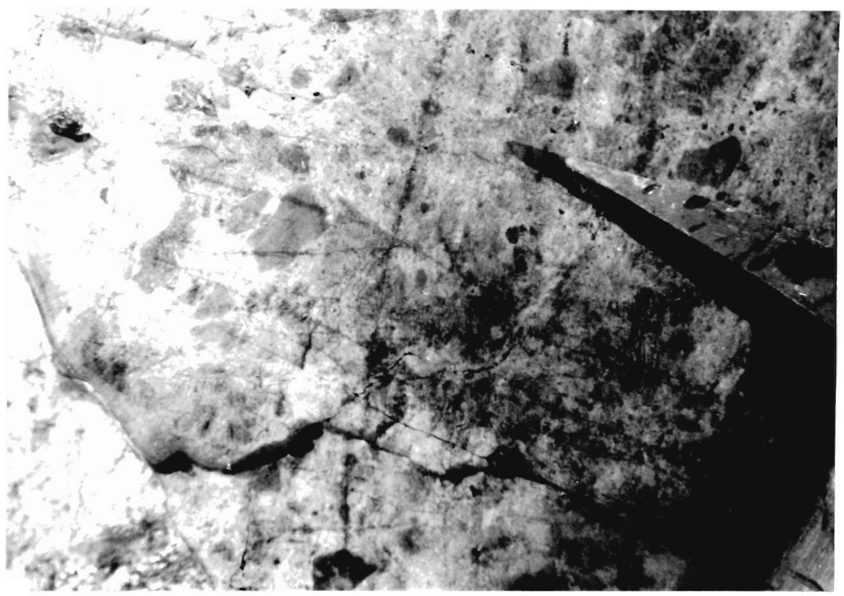


Fig. 73 - Dark rounded to subangular fine-grained cognate xenoliths in a fine-grained syenite of the intermediate group.

an igneous breccia (fig.73, p.172). The porphyritic olive grey syenite of the intermediate group has a similar appearance to the xenolithic material, and at Lac Salé it forms medium-grained contact zones of a coarse-grained pale yellowish brown syenite (fig.25, p.88).

The intrusives containing cognate xenoliths are of nearly equivalent age and provide some clues as to the conditions prevailing at the time. The cognate xenoliths show no relation to the rocks intruded and are often represented in no other form than as inclusions. They are believed to have crystallized rapidly when the magma intruded relatively cool rocks, but were broken up and partly assimilated by further movement in the magma. They might be considered remnants of a chilled phase.

Xenocrysts and phenocrysts

It is not an easy task to prove that a foreign crystal of perthite in an alkali syenite is a xenocryst as its composition is the same as that of the felspar of the host rock. Well-developed cleavage in the felspar imparts a euhedral form to crystals plucked from the walls of intrusions. In this study large felspar crystals are treated as phenocrysts unless proved otherwise.

A common feature of the porphyritic syenites of the Mutton Bay intrusion is the zoning of the large felspar crystals. The border zone of these crystals is like the felspar crystals of the matrix but their cores differ in various ways. They may be less un-mixed, contain a greater or lesser number of inclusions than the rims, and have a potash felspar component with a different 2V . In some cases there is a gradation between zones but in others there is a sharp separation with the core having a rounded and corroded outline (figs.40 and 41, p.121). While these features could apply to phenocrysts or xenocrysts, a corroded core strongly suggests that the core is a xenocryst. Inclusions found in the zoned felspar crystals increase in size towards the rims, and the inclusions, when confined to the cores, indicate a rapid rate of crystallization followed by a slower one, and the reverse when the inclusions are confined to the rims.

Felspar crystals filled with small mafic inclusions are common to members of the intermediate group especially the medium-grained very well foliated grey syenite, the porphyritic olive grey syenite, and some of the fine-grained and porphyritic syenites. They are also typical of cognate xenoliths in the outer cone sheets of the early group.

In the case of the outer cone sheets the large felspar crystals have corroded inclusion-filled cores identical with the felspar found in the xenoliths, and from which they were no doubt derived. The large felspar crystals of the fine-grained light olive grey foliated pyroxene syenite have inclusion-filled cores but these are not corroded and are believed the result of a change in the rate of crystallization. They are phenocrysts. The porphyritic olive grey syenite has inclusions concentrated around the rims of the large felspar crystals with the cores free of inclusions. These again are phenocrysts which started crystallizing before the mafics but enclosed the latter as soon as they appeared. The first two members of the grey felspar subgroup, the medium-grained grey syenite porphyry and the medium- to coarse-grained well foliated grey syenite, have mafics enclosed in the felspar. Inclusions are particularly concentrated in the cores of very large crystals but the cores are not corroded and the distribution of inclusions indicates a change in the rate of crystallization. In the third member of this subgroup, the medium-grained very well foliated grey syenite, the cores of the large felspar crystals contain a few inclusions and are corroded and surrounded by borders filled with numerous inclusions. The corroded cores are derived from the disintegration of xenoliths of earlier members of the subgroup (fig.74).

Many of the early porphyritic syenites of the intermediate group contain large felspar crystals that can be matched with felspar in the early coarse-grained massive syenite country rock. X-ray diffraction shows that the potash component of the red 'phenocrysts' is orthoclase-rich and of the green ones microcline-rich, suggesting that the red ones are xenocrysts derived from early massive syenite and that the green ones are possibly phenocrysts. This is not conclusive as the potash component of the groundmass felspars in rocks containing 'phenocrysts' is also orthoclase-rich, but the groundmass may be composed also to a large extent of early xenolithic felspar. It is interesting however that the potash component of the green 'phenocrysts' in one case is less microcline-rich than that of the groundmass felspar, indicating that even the green ones could be xenocrysts.

The contact of a medium-grained grey porphyritic syenite with massive coarse-grained green syenite is shown in fig.75. The younger porphyritic syenite has a strong flow foliation parallel to the contact and between it and the older massive variety is a

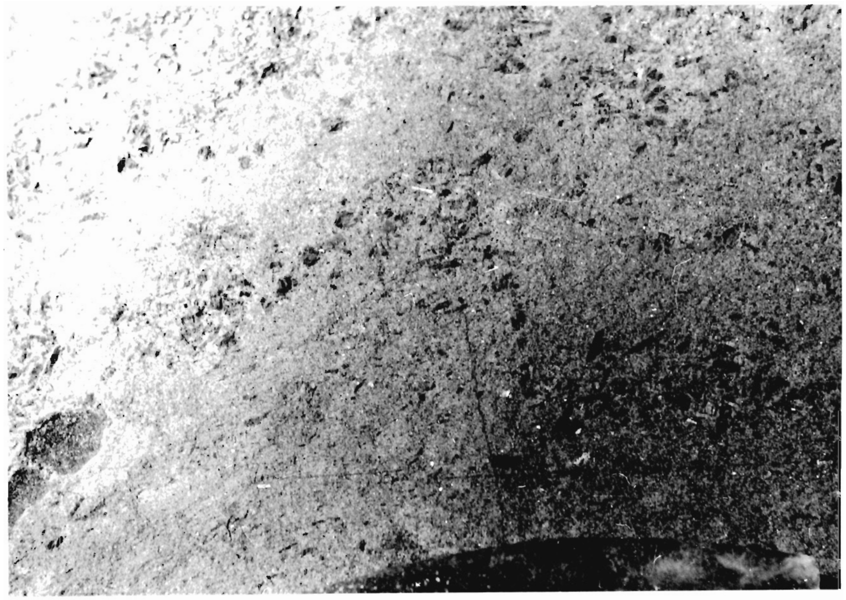


Fig. 74 - Xenoliths of medium- to coarse-grained well foliated grey syenite in medium-grained very well foliated grey syenite. Crystals (dark) are being dragged from the disintegrating xenoliths into the host.

Fig. 75 - Contact between coarse-grained massive green pyroxene syenite (top) and younger medium-grained foliated porphyritic syenite (bottom). A mafic-rich zone containing xenoliths and xenocrysts of the massive variety separates the two varieties.

mafic-rich zone containing inclusions and xenocrysts plucked from the massive syenite. The large felspar crystals are dragged into the younger syenite while the finer-grained and possibly melted mafics are left behind. The contact of the mafics with the massive syenite is irregular, while that with the porphyritic syenite is straight. Compare this to fig.85 (p.188). Similar mafic concentrations were observed at the contact of a porphyritic syenite with a medium- to coarse-grained well foliated syenite on Île Verte, and at the contact of a porphyritic syenite with a coarse-grained massive syenite on Cedar Island.

It is clear that many, if not most, 'phenocrysts' found in rocks of the Mutton Bay intrusion are in fact xenocrysts. This has an important bearing on the conditions prevailing at the time of intrusion. The magma must have been hot enough to partially melt and break up the country rock, and was fluid enough to allow xenocrysts to be dragged away from the contacts. The rocks of the late group which are not porphyritic intruded as a crystal mush at a lower temperature and did not affect the country rock to the same degree. The fine grain size of members of the intermediate group is not necessarily the result of rapid cooling. The abundant xenocrysts would increase the rate of nucleation and so result in a generally finer grain size for rocks of the group.

Magmatic flow phenomena and differentiation

The Mutton Bay intrusion abounds with structures resulting from flow of magmas and crystal mushes, and displays considerable evidence of crystal and chemical fractionation.

Flow differentiation and igneous contacts

Bhattacharji and Smith (1964) demonstrated experimentally that flow differentiation is capable of causing crystal and chemical fractionation in nature. In applying the mechanism to explain the chemical and mineral distribution in the feeder dyke of the well-publicized Muskox intrusion, they brought a very important concept into petrologic thought. Baragar (1960) had earlier applied the concept to explain the absence of plagioclase phenocrysts in the margins of certain sills in Labrador. The concept has since been used in petrology by others, including Buddington (1966) who uses it to explain the differentiation of the Adirondack anorthosite mass. Recent experimental work by Bhattacharji (1967) concerns the mechanics of flow differentiation in ultramafic and mafic sills.

The basic principles of flow differentiation are outlined by Bhattacharji and Smith (1964) and can be found in textbooks of fluid mechanics. Basically, segregation of solids takes place in a solid-fluid mixture away from the walls and towards the central axis of a conduit. The rate of inward movement increases with particle size. The total effect is to produce a fine-grained contact and coarse-grained core.

Flow differentiation is not the only mechanism operating in a solid-fluid system. Gravity is perhaps the most important mechanism causing differentiation and in most cases masks the effect of flow differentiation. Its effects are obvious and need not be dealt with any further here. Flow differentiation is intimately concerned with the contacts of igneous bodies, but so is chilling, and the two concepts should not be confused.

Chilled contacts

Chilling of a magma at its contacts to produce a fine-grained rock is a concept taken for granted by most geologists. The effect of chilling however is not clearly understood so will be looked at more closely. Chilling under static conditions is the simple case. However, chilling implies movement of the magma in bringing it to the surface where it is to be chilled. Thus, while simple cooling of a magma at its contacts may be studied experimentally, it is not chilling in the geological sense.

If a melt is cooled without agitation, the first crystals to form are at the contacts which cool first and also provide seeds which encourage crystallization. Crystals are confined and can grow unhindered in only one direction as demonstrated in Tammann's (1925, and described by Buckley, 1951, p.71) method of growing crystals. Crystals favourably oriented with their direction of fastest growth perpendicular to the walls of the container will grow unhindered, but squeeze out crystals not so favourably oriented. The result is a fine grain size at the contacts. An example of this type of crystallization is the late aegyrine-hydronepheline dykes (fig.67, p.162). It must be noted that there was no movement or agitation of 'magma' in Tammann's (1925) experiments, and presumably there was none in the natural examples cited. When crystals have no strong preferred direction of growth the results are less spectacular. Another factor may lead to the formation of a fine-grained contact in this sort of crystallization. The wall rock of an intrusion offers many irregularities which can act as seeds for crystallization, but the first layer of new crystals will have less irregularities and there will be less seeds and as a result fewer crystals will form.

When dealing with intrusions that show evidence of flow account must be taken of the fact that the liquid is being agitated and therefore the nucleation rate is increased. Matusevich (1959) concluded from experiments that increasing the stirring (agitation) meant the falling off smoothly of mean crystal size. The greatest relative movement in a flowing magma is in the contacts and so, if we assume that nucleation occurs throughout the dyke nearly simultaneously, as might well be the case, there will be a greater rate of nucleation at the contact than further away. This would result in a finer grain size at the contact.

It can be seen that several mechanisms all result in the same distribution of grain size across a dyke. Arguments for one or other mechanism must be carefully weighed as some attempt must be made to determine which mechanism applies. Simply describing a fine-grained contact as chilled should be discarded except when the contact is glassy. In all probability more than one mechanism is operating in any one instance. While the actual mechanism is not always important, problems do come up which may be solved if the correct mechanism is appreciated.

Lineation

Several kinds of lineation are found in the Mutton Bay intrusion. They all result from flow in a magma and include elongated minerals and clusters of minerals, elongated xenoliths, axes of rotation of crystals, and pinch and swell structure.

<u>Mineral lineations</u> : Mineral lineations are best developed in the intermediate and late groups of intrusives. The magma was restricted in these groups by relatively closely spaced walls and therefore was subjected to strong differential flow.

Minerals giving rise to lineations are amphibole prisms and felspar plates. Clusters of mafic minerals interstitial to felspar laths that have been rotated about a linear axis also have a linear orientation. Amphibole prisms show a good linear orientation in mafic-rich concentrations which are only thin films in the intermediate group or 1-3 inches thick in the late group. Clusters of mafic minerals in the medium-grained very well foliated grey syenite result in a weak lineation. Fig.76 is a section parallel to the foliation plane and fig.77 is a section perpendicular to the lineation. Felspars of the late group of intrusives have an excellent linear orientation (fig.78). It is only seen on foliation planes which are not easy to find in these coarse-grained rocks as outcrops are rounded both by ice action and recent weathering, and foliation joints are not prominant.

Lineations measured are presented in a contoured lower hemisphere projection (fig.80). All plunges are towards the centre of the pluton down the dip of the foliation and therefore the projection may be used in a geographical as well as a strictly statistical sense. The girdle is incomplete as it only represents the west half of the pluton where the average plunge of lineations is 45-55°.

<u>Axis of rotation of felspar crystals</u> : Felspar plates in the very well foliated coarse-grained syenite of the late group rotate

Fig. 76 - Medium-grained very well foliated grey syenite with a lineation of clusters of mafic minerals on the foliation plane. Arrow indicates lineation.

Fig. 77 - As in fig.76 but a section perpendicular to the lineation.

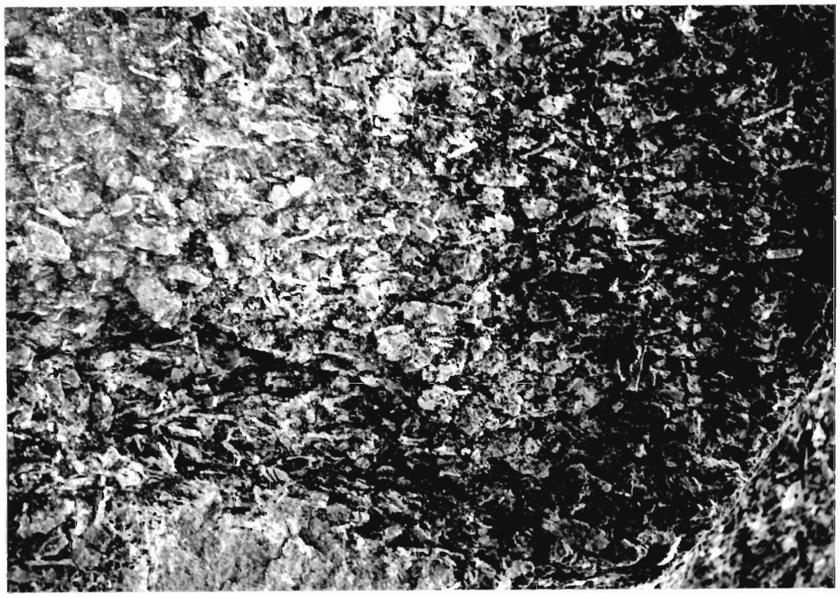


Fig. 78 - Coarse-grained very well foliated pink syenite showing a lineation of felspar laths on the foliation plane.

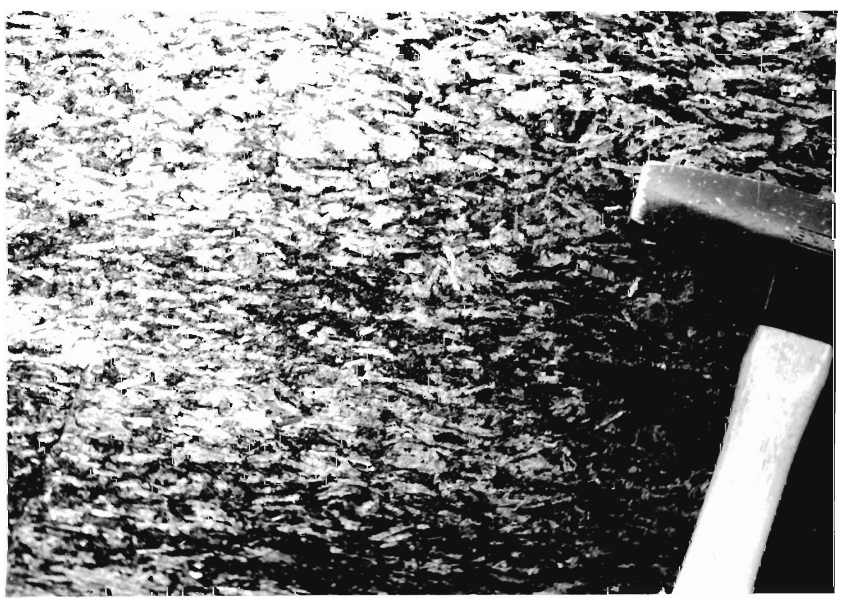


Fig. 79 - As in fig.78 but a section perpendicular to the foliation and parallel to the lineation.

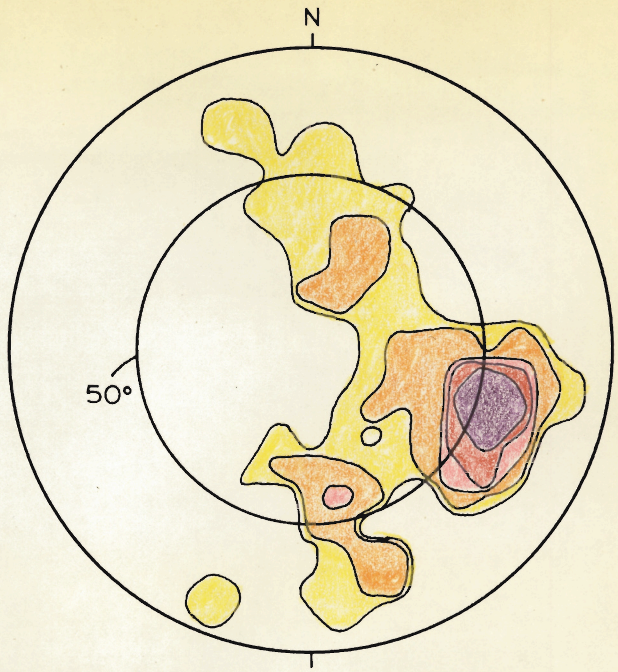


Fig. 80 - Contoured lower hemisphere equal area projection of 63 lineations in the Mutton Bay syenite pluton. Points cover the west half of the pluton and form an incomplete girdle of lineations plunging 45-55°. The 50° girdle is shown. Contours : ½, 1, 2, 3, 4, 5% per 1% area

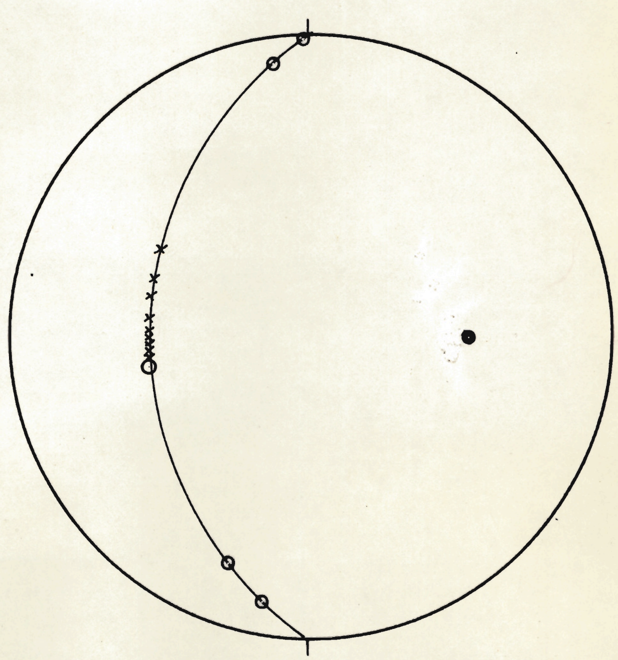


Fig. 81 - Composite (upper hemisphere) stereographic projection of 4 areas showing relation of fold axes (o) and mineral lineations (x) to the foliation plane (pole to foliation plane ●). In each case the foliation planes have been rotated to the same strike and dip.

about an axis parallel to the lineation, as demonstrated by comparing fig.79 (p.183), a section at right angles to the foliation plane and parallel to the lineation, with fig.82, a section at right angles both to the lineation and foliation.

Pinch and swell structure and other flow folds : Pinch and swell structures and flow folds (fig.83) are seen at a number of places. They occur where coarse-grained very well foliated pink syenite of the late group has intruded medium-grained very well foliated grey syenite of the intermediate group. The country rock was heated and perhaps partially melted and, because of its finer grain size, behaved incompetently. Buckling or stretching of the finer material gave rise to folds and pinch and swell structures as found in metamorphic rocks.

Axes of the flow folds and pinch and swell folds are at right angles to the mineral lineation or direction of maximum flow. Fig.81 (p.184) is a composite stereographic projection of mineral lineations and fold axes with respect to the foliation plane of four cases studied. The foliation plane in each case has been rotated about the vertical axis and a horizontal axis in the foliation plane so that the foliation planes coincide.

Foliation

Foliation is developed to varying degrees in most units of the syenite pluton. The early massive varieties show the poorest development but a weak foliation can often be seen on good exposures.

The massive green syenites have a greater tendency to develop a preferred orientation than the massive pink syenites which have a more granular (granitic) texture. In the latter, however, narrow pink stringers parallel the weak foliation and emphasize it. The

Fig. 82 - As in figs.78 and 79 but a section perpendicular to foliation and lineation.

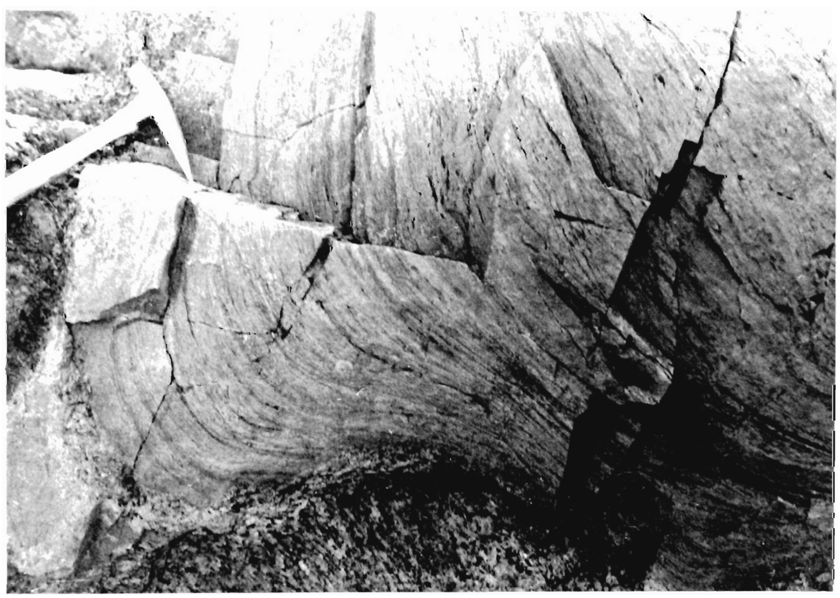


Fig. 83 - Medium-grained very well foliated grey syenite cut by coarse-grained very well foliated pink syenite. Folding in the finer material results from a greater incompetency with respect to the coarse material because of the difference in grain size and partial melting in the finer material.

stringers are the result of alteration of the felspar along fractures by hydrothermal solutions and apparently formed easiest parallel to the weak foliation. These fractures may be the result of cooling or may be shears that formed after consolidation. Foliation in the early massive rocks is parallel to the contacts with the gneisses and is vertical or steeply dipping towards the centre of the pluton.

Following the intrusion of the massive syenites are a great variety of intrusives, the majority of which exhibit a well-developed foliation. The more platy the felspars the better the foliation and many rocks may be described as having a trachytoidal texture. The better foliated rocks are generally contained between closely spaced walls. Foliation is parallel to the contacts and is a flow foliation developed in a crystal mush rather than a crystal settling feature.

Flow layers (lines) : Flow layers are best developed at solid-fluid contacts where differential flow is greatest. This is well illustrated in fig.84 where magma has flowed between two large solid blocks with the development of foliation at the contacts. Flow layers are smooth and wrap around inclusions with the gaps between the inclusions and converging flow layers occupied by disoriented felspar laths. In a similar fashion contacts are covered by smooth flow layers with the irregularities filled by less perfectly oriented felspar laths as seen in fig.85.

Scouring

Scouring is caused by an increase in the rate of flow of an intruding magma with the result that early deposited crystals are dragged back into the liquid to re-establish equilibrium. Deposition of crystals followed by scouring may be repeated several times as

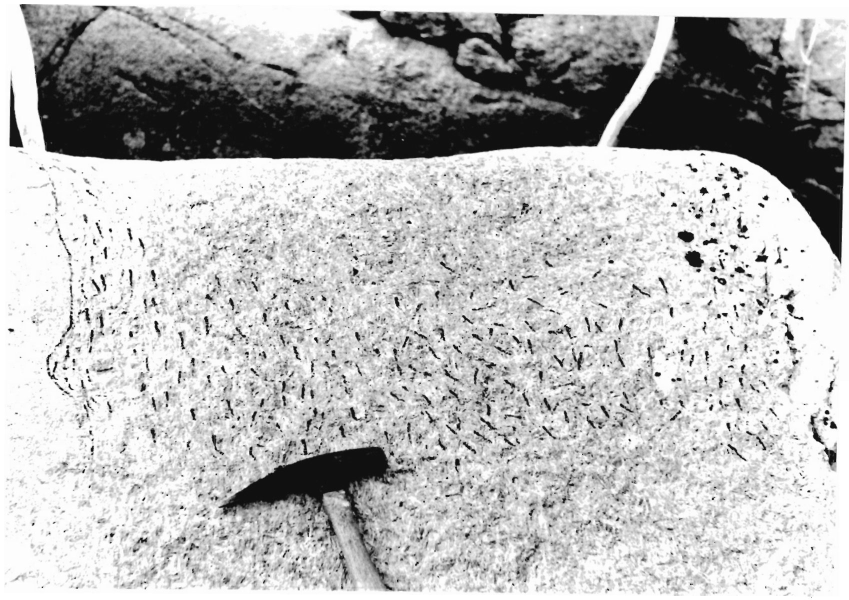


Fig. 84 - Coarse-grained very well foliated pink syenite intruded between blocks of medium-grained pink syenite. Part of the left contact and a representative number of felspar laths are marked in black ink. Flow foliation is well developed at contacts.

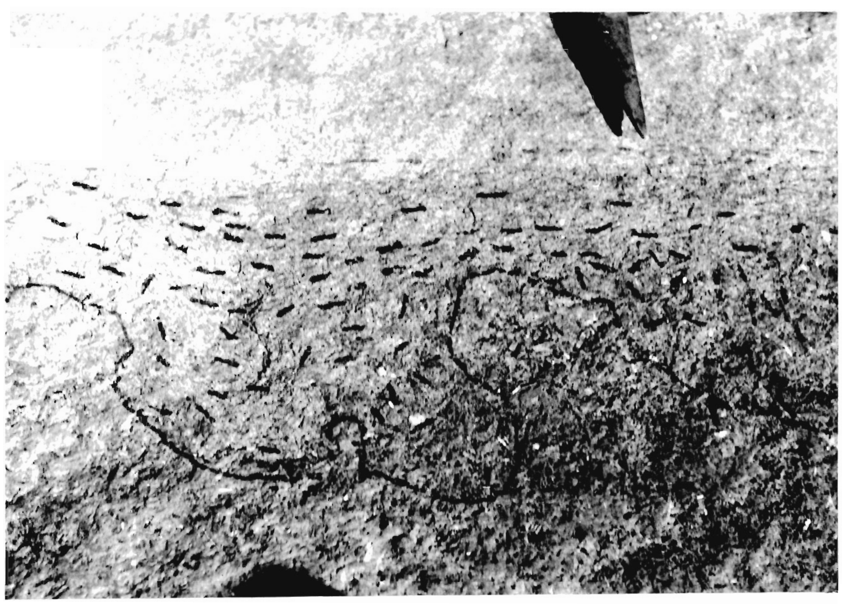


Fig. 85 - Contact of a member of the foliated, sphene-bearing subgroup with coarse-grained massive pink syenite. The contact and a representative number of felspar laths are marked in black ink. Smooth flow lines a few inches from the contact follow the general contact, but close to the contact follow the local irregularities.

shown in figs.86 and 87. Scouring in the above case is along the roof on the north side of the north-dipping younger coarse-grained massive pink syenite at Mutton Bay. Scouring was observed at three points and in each case it indicated that the rock to the south was the younger. A slight enrichment of mafics in the trough of the scoured channels probably accumulated as a result of the relative small size and density of the mafic constituents compared to large light felspar crystals that are dragged into the fluid more easily. It may also represent a contact accumulation of late mafic liquid. The floor of the same intrusion does not exhibit scouring but does show a greater accumulation of mafics some of which injected the foot-wall as in fig.88.

Scouring is spectacularly developed at Lac Salé where a mafic-rich hybrid of the coarse-grained very well foliated green syenite is scoured by coarse-grained very well foliated pink syenite (fig.89). The former exhibits rhythmic layering, indicating varying flow conditions. Scouring by the pink variety represents a very marked increase in the rate of flow, which in most cases has completely scoured away the early green mafic hybrid.

Differentiation

Differentiation has been clearly demonstrated in the chemical study of the pluton and it is strongly suggested that two processes are involved, one gravity settling, and the other filter pressing. Magmatic flow strongly influences both processes but particularly the latter.

Quantitative mineralogical evidence of differentiation : The Mutton Bay syenites are unique in that the felspar composition remains

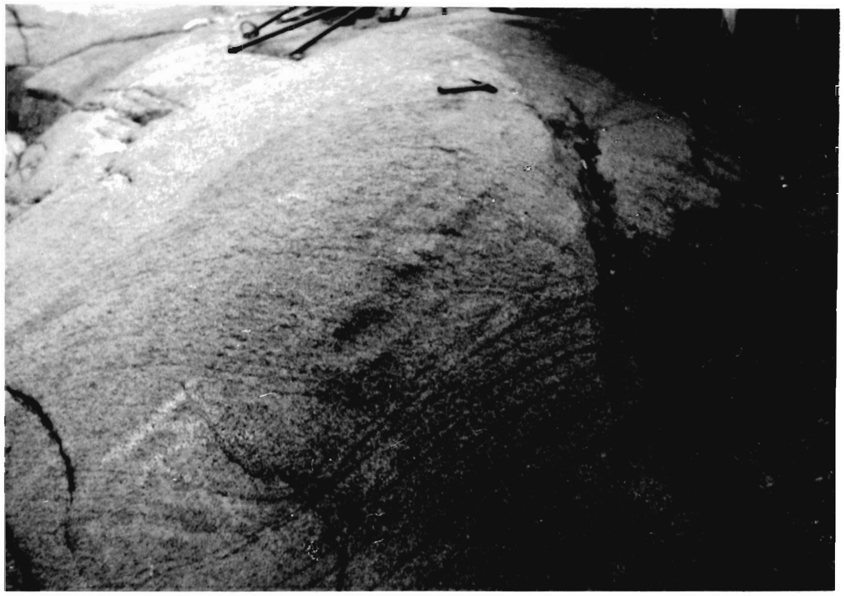


Fig. 86 - Scouring in the hanging wall of the younger coarse-grained massive pink syenite at Mutton Bay. Rhythmic banding at left is truncated by that at right.

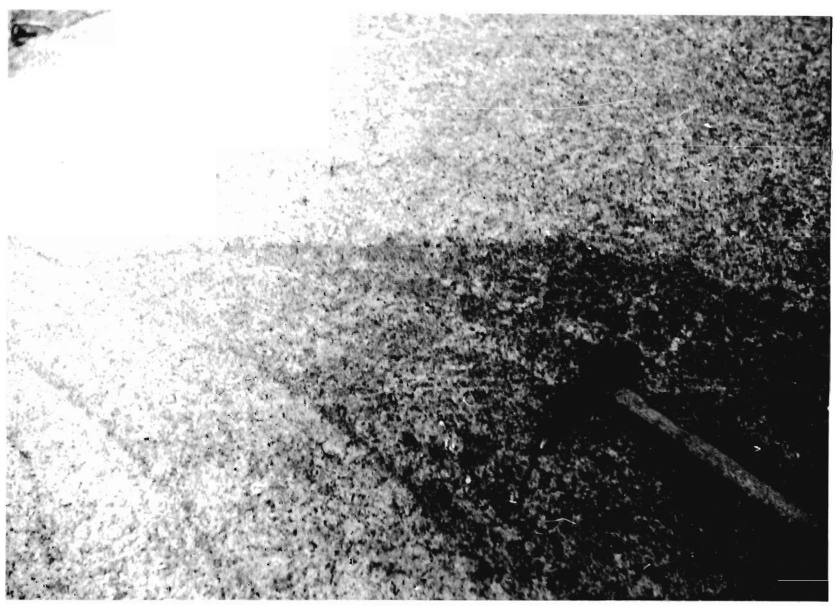


Fig. 87 - As in fig.86 but showing the truncation of a layer on the right by others on the left in greater detail.

Fig. 88 - Accumulation and injection of mafics into the foot wall of the younger coarse-grained massive pink syenite at Mutton Bay. Contact with the older variety is marked in ink.

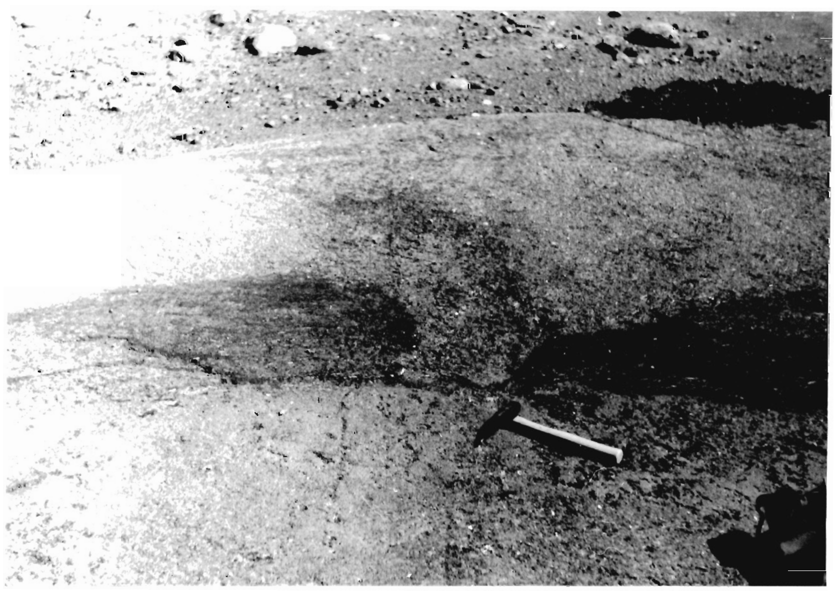


Fig. 89 - Coarse-grained very well foliated green mafic-rich syenite (dark) cutting medium- to coarse-grained very well foliated grey syenite (foreground) and scoured by coarse-grained very well foliated pink syenite (background). Rhythmic layering is visible in the mafic-rich syenite. All rocks dip towards background.

nearly constant during differentiation, with only the mafic constituents varying chemically. The system undergoing differentiation is simpler than most and the only important differentiation process taking place is of a mechanical nature.

If the percentage perthite is plotted against the remaining mineral components in the modal analyses of Mutton Bay rocks, it is possible to get some idea of the mechanism causing separation of the minerals. If the percentage early euhedral crystals such as olivine, pyroxene, apatite, and magnetite are plotted against perthite (fig.90) no variation is evident, showing that there was no generally effective separation of early mafic minerals with respect to felspar. If the percentage late anhedral ferromagnesian minerals, amphibole and biotite, are plotted against perthite (fig.91), there is a clear relation between the two. The slope of the curve is about .7, showing that mechanical differentiation is directly between late ferromagnesian minerals and perthite.

The felspars in these very felspathic rocks started crystallizing in large quantities at the same time or perhaps before the early ferromagnesian minerals, and did not allow any generally effective separation of early minerals to occur by gravity settling except at the very start of crystallization. The coefficient of variation of P_2O_5 analyses (p.117) indicates that the apatite was concentrated by gravity before there was much interference by felspar. The late crystallizing ferromagnesian minerals, amphibole and biotite, crystallized after the felspars and were effectively concentrated as residual liquids.

<u>Flow differentiation</u> : Most mafic concentrations in the pluton can be ascribed to gravity settling. A study made on a number of inclined (45° to 80°) dyke-like intrusions of coarse-grained very

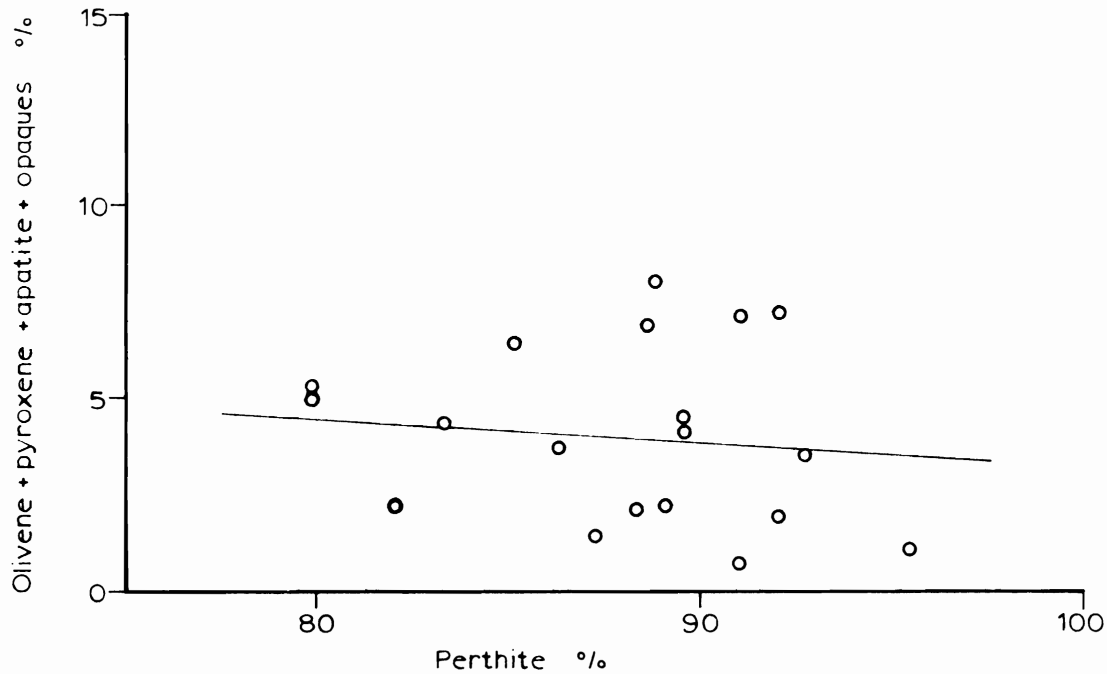


Fig. 90 - Variation in content of early crystallized mafic minerals (olivine + pyroxene + apatite + opaques) with respect to early crystallized perthite.

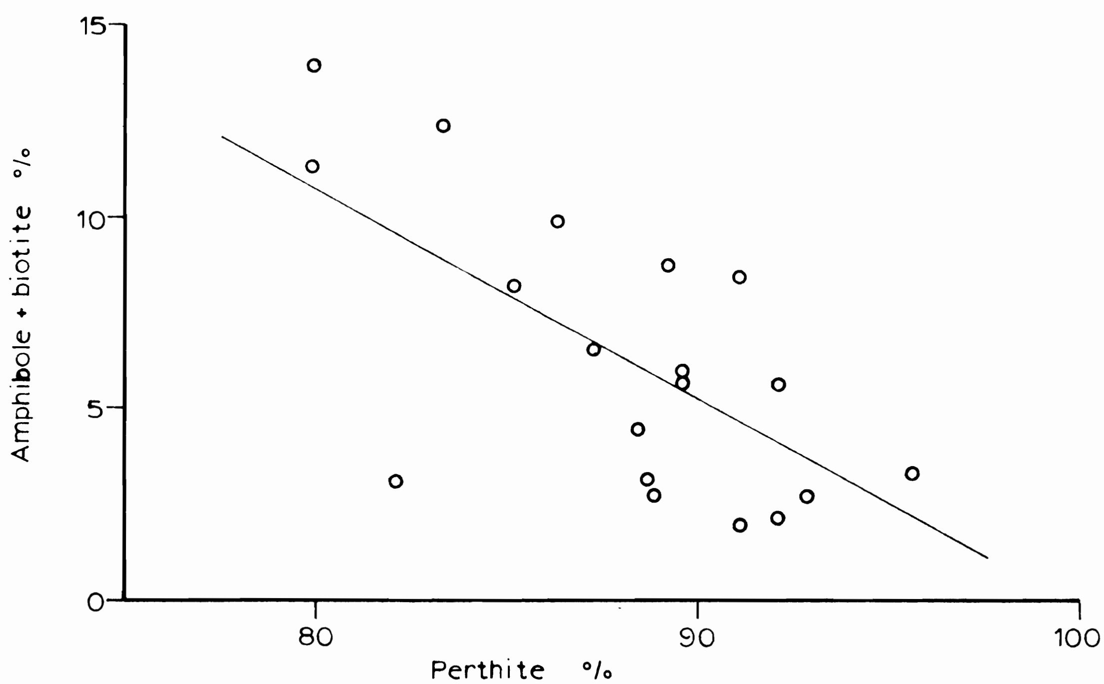


Fig. 91 - Variation in content of late crystallized mafic minerals (amphibole + biotite) with respect to early crystallized perthite.

well foliated pink syenite shows that a roof concentration of mafics, in addition to one on the floor, was sometimes present. The latter was about 10 times as thick as the former. Concentration of mafic minerals on both floor and roof of the younger coarse-grained massive pink syenite of Mutton Bay has already been mentioned. The generally steep dip of the rocks is believed the reason for the roof concentrations, because the effect of gravity becomes less important and features characteristic of vertical dykes and pipes begin to appear.

An example of a differentiated sequence with a roof concentration was studied in some detail, and fig.92 shows the mineral variation from roof to floor. Distances were paced along the seashore and are approximate. Pyroxenes are concentrated on the floor whereas amphiboles are concentrated at both contacts in nearly equal amounts. This mineral distribution indicates that pyroxenes were concentrated by gravity settling and that amphiboles crystallized from a residual mafic liquid that was concentrated by flow differentiation in the sheared contacts. The sudden increase in felspar one foot above the floor is not believed to have any significance.

Gravity differentiation : There is no doubt about the action of gravity in the formation of many mafic segregations. Gravity is the main factor involved in the floor accumulations of mafic minerals though flow differentiation was also involved. Bottom concentrations include those on top of xenoliths which act as false bottoms.

The most spectacular mafic concentrations are found in the

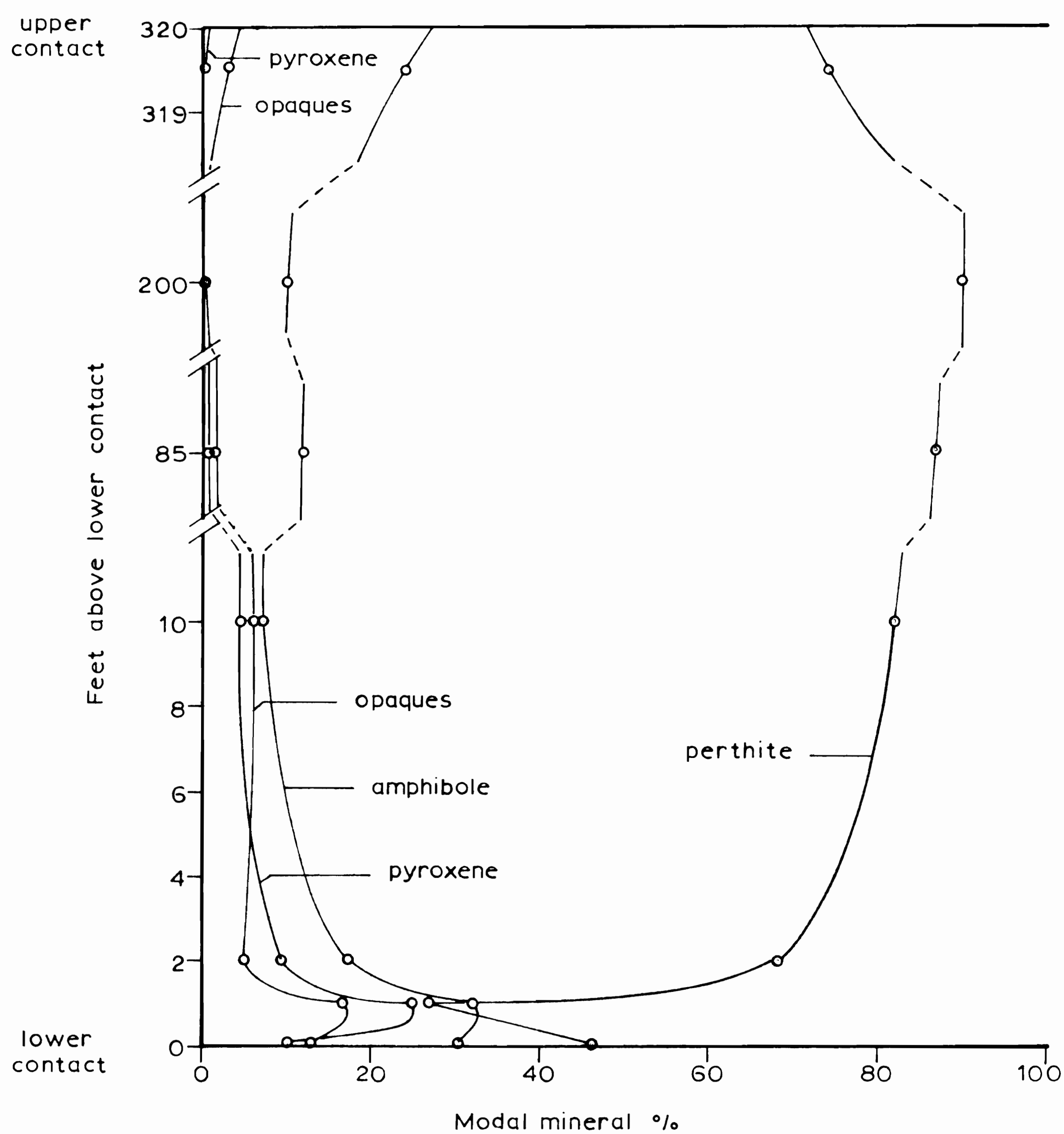


Fig. 92 - Variation in percent of modal minerals across a sequence of coarse-grained greyish orange pink very well foliated syenite dipping 45°.

coarse-grained very well foliated syenites. Concentrations in the pink variety generally contain pink felspar crystals and the mafic minerals are essentially amphiboles. The example studied in detail above is an exception. Mafic concentrations containing green felspar are rich in pyroxene and/or olivine.

Amphibole concentrations in the pink syenites are often composed entirely of mafic minerals over narrow widths. Concentrations are irregular and figs.93 and 94 show a moderate concentration in coarse-grained very well foliated pink syenite that varies from 4 feet to 1 inch thick over a very short distance. Coarse-grained very well foliated green syenites display thicker mafic concentrations and are more spectacular because of a sympathetic change in colour of the felspar. Figs.95 and 96 are of an excellent example, and one in which the differentiated sequence has been cut by a younger series of concordant sheets of coarse-grained very well foliated mafic-poor green syenite.

In places there are repeated sequences of mafic-rich syenites grading up into mafic-poor syenites, each sequence indicating a pulse of injecting magma (fig.97). In such a case the total number of pulses cannot be determined as it is complicated by the presence of large blocks of country rock creating false bottoms, and the fact that one pulse may be represented by intrusions at different levels (fig.98).

Injection of mafic concentrations into the foot-wall is common and veins of mafic minerals occur apparently unrelated to any large mass. The fact that mafic minerals inject the foot-wall as veins indicates that there was no rapid chilling at the contacts and the mafic segregation was at least partially liquid.

Fig. 93 - Moderate floor accumulation of mafics 4 feet to 1 inch thick in coarse-grained very well foliated pink syenite cutting an earlier phase of the same rock. Contact and flow foliation dip left.

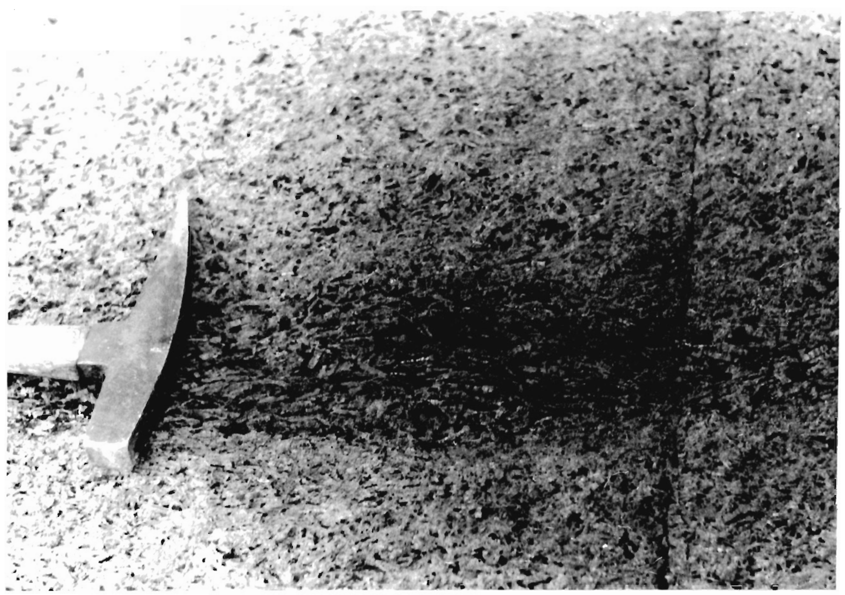


Fig. 94 - As in fig.93 showing detail of the contact. Foliation dips towards top of picture.

Fig. 95 - Coarse-grained very well foliated green syenite showing an increase in mafics to the right and cut by concordant sheets of coarse-grained very well foliated mafic-poor green syenite. Layers dip to the left.

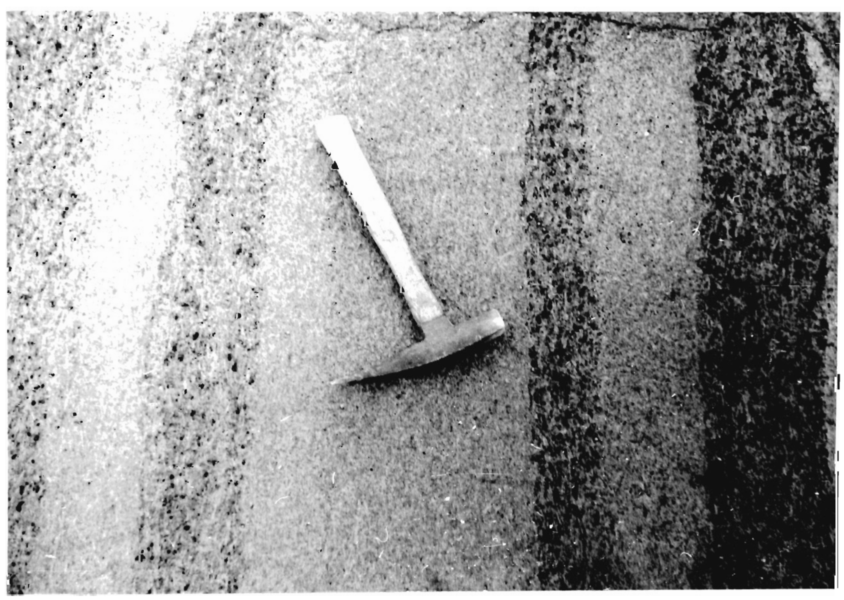


Fig. 96 - As in fig.95 but showing details.

Fig. 97 - Coarse-grained very well foliated syenite showing repeated mafic accumulations to the left.

Fig. 98 - Coarse-grained very well foliated pink syenite (dark) cutting medium-grained very well foliated grey syenite.

Temperature-pressure conditions during crystallization of the Mutton Bay intrusion

All the Mutton Bay intrusives are hypersolvus single felspar rocks that have exsolved to a microperthite. Oligoclase is present as a separate felspar phase in the coarse-grained massive pyroxene syenite of the early group, but the oligoclase crystals are believed to be xenocrysts derived from the assimilation of the country rock.

In the Mutton Bay rocks there is up to 3 percent anorthite molecule in the felspar of the intermediate and late groups and larger amounts in felspar of the early group. Parsons (1965) reasoned, for similar hypersolvus rocks of the Loch Ailsh intrusions, that the possible range of temperatures of crystallization is defined for the composition concerned by the solidus in the ternary felspar system at zero water-vapour pressure, and the temperature of the intersection of solidus and solvus at higher pressures. Taking the line for the limit of immiscibility as that shown by Tuttle and Bowen (1958, p.132) he concludes that for the compositional range concerned 1 percent An raises the solvus by about 40°C.

The felspars of the Mutton Bay rocks are less sodic than those of the Loch Ailsh intrusion. However, a section can be drawn perpendicular to the base of the temperature-composition prism of the ternary felspar system so as to include the minimum temperature position on the approximate line of the limit of solid solution in the Tuttle and Bowen diagram (1958, p.132) and to intersect the $NaAlSi_3O_8$ - $KAlSi_3O_8$ face of the prism at a composition of $Ab_{60}Or_{40}$, the general composition of the felspars of the Mutton Bay intrusion. This section intersects the solvus very near its maximum value for water-vapour pressures of 980 bars (Tuttle and Bowen, 1958, p.40) and 5000 bars (Yoder, Stewart, and Smith, 1957, p.208). The top of the solvus is fairly flat over the range of composition of the Mutton Bay felspars. Orville (1963) determined the solvus at 2000 bars water-vapour pressure in the presence of 2M alkali chloride solution. This solvus was used by Parsons (1965), perhaps because it has its maximum value within the compositional range of the Loch Ailsh felspars. However, its shape is different to those determined at 980 bars and 5000 bars water-vapour pressure and should not be used in calculations and compared with the solidus and solvus values that were determined without the presence of alkali solutions. The shape of the solvus in the ternary felspar system is not known and it is assumed to vary linearly with An content.

The solidus in the $NaAlSi_3O_8$ - $KAlSi_3O_8$ system has been determined by Tuttle and Bowen (1958, p.40) for water-vapour pressures of 0, 490, 980, 1961, 2942, and 3923 bars, and by Yoder, Stewart, and Smith (1957, p.208) for a water-vapour pressure of 5000 bars. The solidus in the above cases is fairly flat and the value of the solidus for a composition of $Ab_{60}Or_{40}$ can be taken to be the same as the minimum value. The liquidus in the ternary felspar system is given by Yoder, Stewart, and Smith (1957, p.211) for a water-vapour pressure of 5000 bars, and by Franco and Schairer (1951, p.264) for a dry system, and it is assumed that the solidus varies the same way, which is nearly linearly over the composition concerned for the Mutton Bay rocks.

Fig.99 is constructed with the above data. It can only be approximate as a number of important assumptions have been made, but such an approach is necessary until more data is available.

Using fig.99, the felspar crystallization in the intermediate and late groups of the Mutton Bay intrusion for an An content of 3 percent must have been essentially above 810°C and at a water pressure less than 2700 bars. It might be noted that the depth of the present level below the roof of the intrusion has been estimated to be 9.5 - 13 km. (p. 211). Since the roof of the intrusion is believed to have been close to the surface, the load pressure on the rocks being studied was about 3000 bars. This would be the maximum value of the water-vapour pressure.

The early group of Mutton Bay intrusives include rocks with high anorthite content and, besides the sample containing oligoclase xenocrysts, samples of both green pyroxene-syenite and pink syenite plot on the limit of solid solution for dry magmas. High temperatures and low water pressures (less than 500 bars water pressure) are necessary for these rocks. Using the normative felspar of the rock analyses, a maximum anorthite content of 8 percent indicates temperatures of greater than 1015°C and a water pressure of less than 500 bars. The striking lack of biotite in the intermediate group, enrichment in Fe (Osborn, 1959), and the lack of extensive un-mixing of the alkali felspars, also supports the contention of a dry magma.

Anatexis during intrusion

The effect of the very dry magma and high crystallization temperature on the relatively dry country rocks is of great

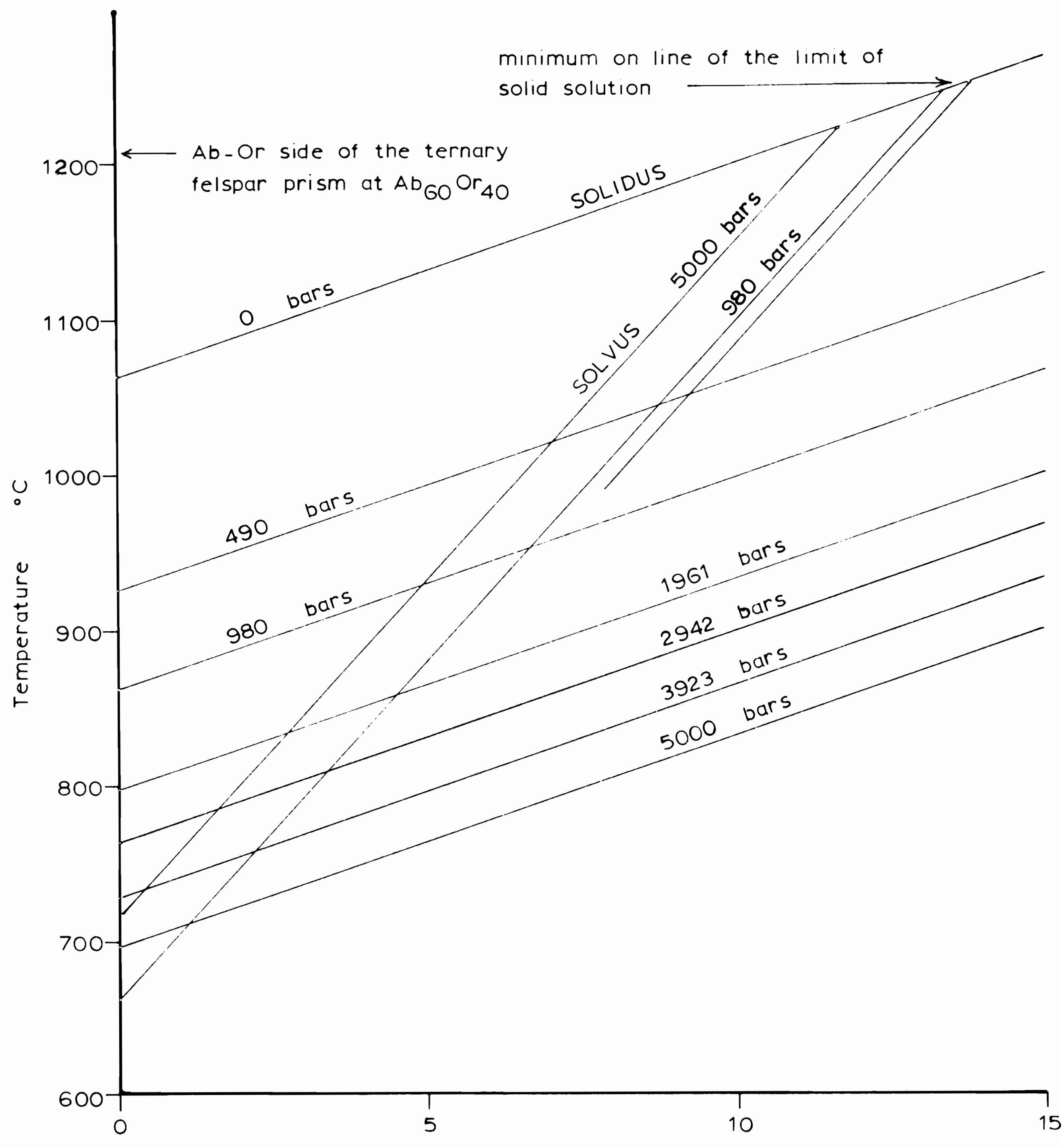


Fig. 99 - Section through the temperature-composition prism of the ternary felspar system including the minimum on the line of the limit of solid solution in the Tuttle and Bowen diagram (1958, p.132) and the composition line $Ab_{60}Or_{40}$ on the $NaAlSi_3O_8$ - $KAlSi_3O_8$ side of the prism. It is assumed that the solvus varies linearly with anorthite content and the solidus is assumed to vary in a similar way to the liquidus in the ternary felspar system. The liquidus which is given by Franco and Schairer (1951, p.264) for the dry system and by Yoder, Stewart, and Smith (1957, p.211) for a water-vapour pressure of 5000 bars, varies nearly linearly over the composition concerned for the Mutton Bay felspars. Solidus and solvus values at 0-3923 bars are from Tuttle and Bowen (1958, p.40) and at 5000 bars are from Yoder, Stewart, and Smith (1957, p.208).

importance. According to Winkler (1965, p.188, after v.Platen, 1965) the eutectic for a gneiss with an Ab/An ratio of about 3 is 700°C at 2000 bars and, applying this value to Winkler's fig.28 (1965, p.168), it should be about 800°C at 500 bars. It has been calculated that the temperature of the contact of an intrusion is somewhat greater than 60 percent of the intrusion temperature plus TC, the temperature of the country rock (Jaeger, 1957). At a depth of 9.5 - 13 km., the depth below the roof of the intrusion (see p. 211), the temperature TC might be about 200°C (Holmes, 1965, p.1004).

The early intrusives reached their present position essentially as a magma rather than as a mush as shown by the general lack of flow foliation. Their felspar crystals started crystallizing above 1015°C and less than 500 bars water vapour pressure and, taking this as a minimum temperature, the country rock temperatures must be 802°C (602° + 200°C or more) which is sufficiently high for anatexis to begin in a relatively dry gneiss. Assuming a water pressure of 500 bars, the felspar crystals of the later intrusives started crystallizing at about 950°C and at lower temperatures for higher water pressures. However, these intrusions reached their present position as a crystal mush so that temperatures were below 950°C but above 810°C (solvus). With a maximum magma temperature of 950°C the country rock temperatures will have a maximum value of 770°C (570° + 200°C) which is hardly enough to cause partial melting even at the immediate contact.

The difference in intrusion temperatures of the early and late magmas is extremely important. It has been shown above that anatexis probably dominated in the early intrusions but was of minor importance in later intrusions.

MODE OF EMPLACEMENT OF THE PLUTONIC ROCKS

The structure of the Mutton Bay pluton is well defined. The early massive syenite has steep to vertical flow foliation near its contacts, and early cone sheets that intruded near the boundaries have fairly steep dips of about 80° towards the centre of the pluton. The late intrusives and the first members of the intermediate group occupy a position between the border and the centre and have shallower dips of 45-55°, but the other members of the intermediate group have steep dips.

There is no undoubted evidence connecting folding in the country rock with intrusion of the syenite, but lineations in the gneisses do swing around the pluton, and some of the folding ascribed to the diapiric granite might have been caused by the younger intrusion of syenite.

Contacts with the gneisses show that blocks of country rock were stoped and dragged into the magma and the acidic material was assimilated. The magma became quartz-rich and contains corroded remnants of oligoclase near the contact. Corroded oligoclase also occurs in some specimens from the centre of the pluton, but here it is not accompanied by quartz. Late inner cone sheets that do not cut the country rock have compositions which indicate that the uncontaminated magma was an augite syenite (nordmarkite).

Faulting has been suggested by many workers as playing an important part in this type of intrusion (Oftedahl, 1959 ; Barth, 1945 ; Harry and Pulvertaft, 1963). The Mutton Bay intrusion is closely associated with a number of large faults which are particularly well-developed northeast of Mutton Bay where most movements are left-handed. The Grande Rigolet fault, which has a large displacement, strikes towards the pluton without cutting it, but there is an apparent kink in the syenite contact at the junction, suggesting a close relation. Other faults undoubtedly exist to the south and may have large enough displacements to provide much of the space required for the pluton. The junction of the Grande Rigolet fault with the syenite of Île Fecteau is also the junction of an outer cone sheet with the contact, which strongly suggests that the faulting accompanied the intrusion of cone sheets.

The mode of emplacement of the Mutton Bay intrusion is complex. Three phases of intrusion must be explained, the initial intrusion of coarse-grained massive green pyroxene syenite, the outer cone sheets, and the inner cone sheets.

Initial phase

The initial intrusion probably provided most of its space by melting the granitic rock ahead of it, becoming granitic itself, and permitting some of the indigestible oligoclase to sink into the magma below. Much of the granite phase probably lay above the present level of erosion but some might have been dragged down by convection to reappear after homogenization with syenite of later intrusives (i.e. quartz nordmarkites). It is interesting to note that similar intrusions in areas in which the present level of erosion is believed close to that of the roof of the intrusions, such as the Oslo, New England, and Greenland areas, are all characterized by the presence of considerable granitic material.

Barth (1945) suggests that the granites of the Oslo region are not a differentiate of the main magma series, and it is possible that this granite is derived from the melting and assimilation of the country rock. In the case of the Mutton Bay intrusion the equivalent granite has been eroded away.

Two possibilities for the size of the initial intrusion are given in fig.100a and b. Fig.100b shows the size of the intrusion needed to account for the present area of massive green pyroxene syenite exposed. Fig.100a is the possible size assuming that much of the massive green pyroxene syenite was assimilated by the massive pink syenite that followed and is shown in fig.100c.

<u>Outer cone sheets</u>

The outer cone sheets all belong to the early group and the first intruded are the coarse-grained massive pink syenites. Dips of flow foliation put the focus of the older coarse-grained massive pink syenite cone sheet at 25 miles, the younger massive syenite at Mutton Bay at 35 miles, and the youngest of the outer cone sheets at 45 miles. Foci of cone sheets do not indicate the depth of a magma chamber but they do suggest that successive intrusions were from greater depths.

The outer cone sheets probably intruded tension fractures that formed parallel to the greatest principal stress axes radiating above the magma reservoir as described by Anderson (1936). Fractures were confined to the initial cylindrical intrusion which was competent with respect to the gneisses.

Both faulting and assimilation are believed to have provided the space needed for intrusion of the outer sheets. Magma that

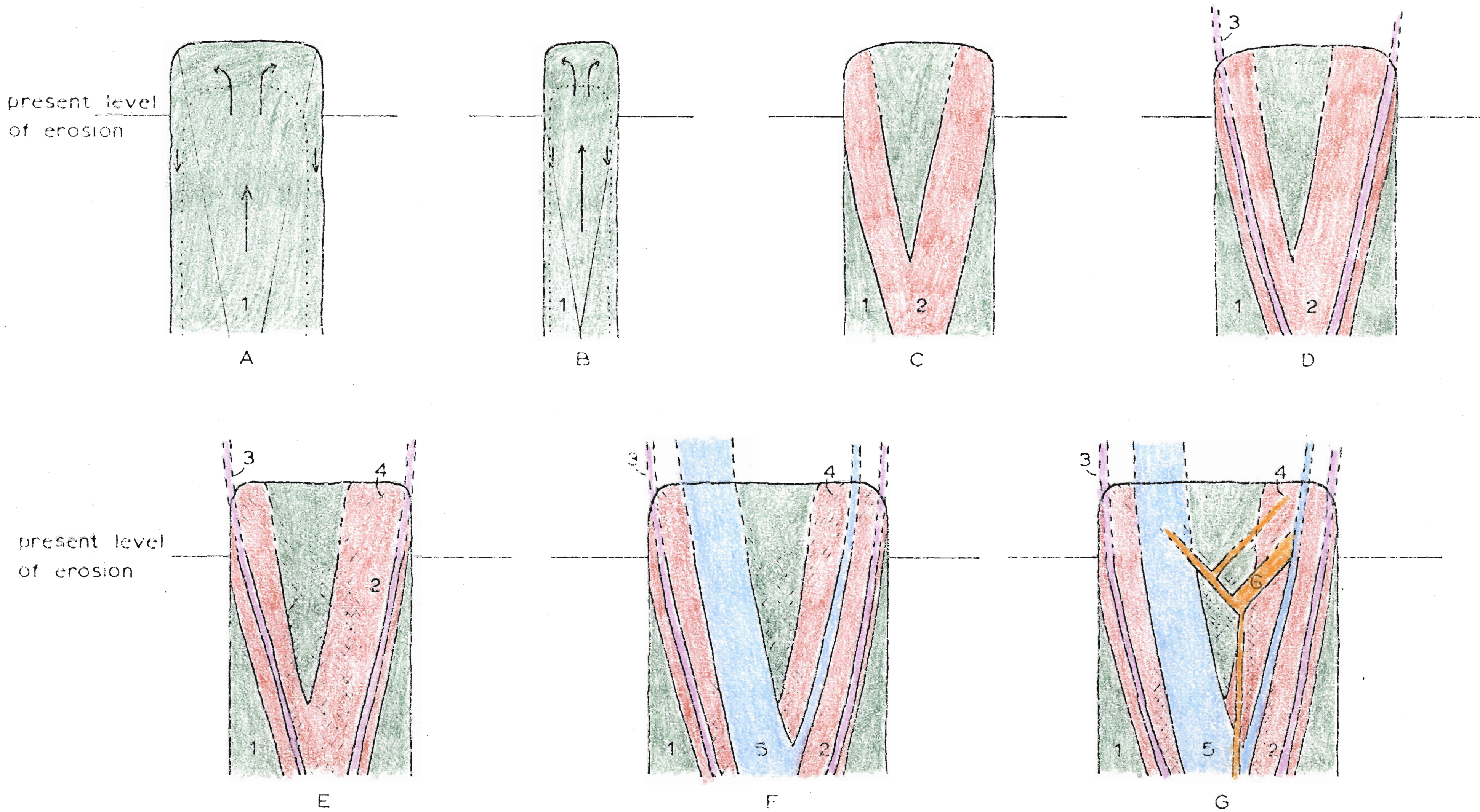


Fig. 100 – Mode of emplacement of the Mutton Bay intrusion shown in successive steps (A-G). Intrusive phases as follows : 1. Coarse-grained massive green pyroxene syenite; 2. Coarse-grained massive pink quartz syenite to syenite; 3. Medium- to coarse-grained green pyroxene quartz syenite and foliated sphene-bearing syenites; 4. Fine-grained syenites and porphyritic syenites; 5. Greenish to pinkish grey granite, porphyritic olive grey syenite and grey sub-group of intermediate group; 6. Late group of intrusives.

formed the coarse-grained massive pink syenite assimilated granitic country rock and the early green pyroxene syenite, and probably obtained most of its space by assimilation (fig.100a and c). Foliated varieties intruded as crystal mushes at lower temperatures, and the space required was probably obtained by faulting in the gneisses with a minimum of assimilation (fig.100d).

Inner cone sheets

The initial phase of the pluton is assumed to have been emplaced as a steep-sided funnel or a cylindrical body 9 miles in diameter. The concentricity of the cone sheets, indicating a single focus, suggests such a shape rather than a mass that broadens downward. The cylindrical or conical plug of relatively brittle igneous rocks enclosed in a relatively incompetent jacket of gneiss was compressed at its ends prior to intrusion of the inner cone sheets. This is essentially the situation existing when cylindrical samples of rocks are compressed in the laboratory, and the results of compression tests on suitable materials might be applied to crystallized igneous plugs.

Theoretically, shear fractures form at 45° to the stress, but in fact the angles are smaller because of friction. In fine-grained material fractures form in zones extending from the edges of the ends of the test piece into the cylinder to form two cones (Nadai, 1950, p.337-338). These cones may penetrate each other, their apices meet at a point, or the apices be separated by a zone of fracturing as shown in fig.101a-c (p.210).

The inner cone sheets of the Mutton Bay intrusion, composed of members of the late group and early members of the intermediate group, dip at angles of 45-55° as is the case in experiments.

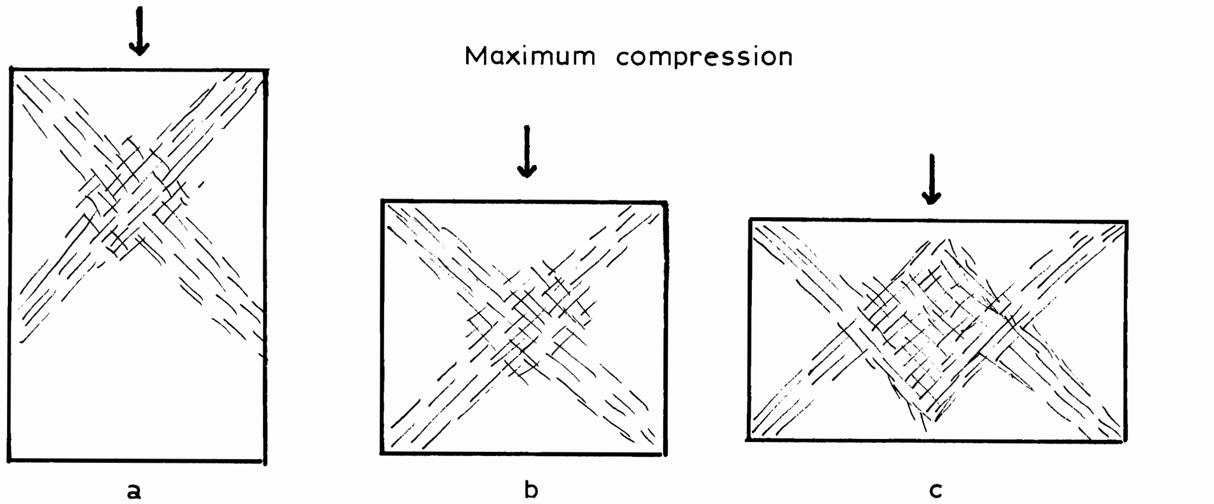


Fig. 101 - Systems of slip lines on the sides of paraffin prisms of same square cross-section and different heights tested in compression. (After Nadai, 1950, p.337).

Their foci are $2\frac{1}{2}$-$7\frac{1}{2}$ miles below the present surface which is much shallower than the foci of the outer cone sheets. The inner cone sheets filled fracture zones (fig.98, p.199) while the outer cone sheets filled single fractures. It is therefore not unreasonable to assume that the inner cone sheets correspond to the zone of shear fracturing found in experiments. Similar fractures due to upward push occur above salt domes (De Sitter, 1959, fig.206 after Behrmann 1949, and fig.207 after Wendlandt 1951).

The early members of the intermediate group intruded the zone of shear fractures as in fig.100e (p.208) but were cut by later members of the intermediate group that intruded tension fractures as steeply-dipping cone sheets and irregular dykes (fig.100f, p.208). The shallow-dipping shear fractures were re-opened and intruded by the late group of intrusions as shown in fig.100g (p.208). Intrusion of the zone of shear fractures in both cases coincides with the onset of a new group of intrusions, suggesting similar stress conditions at these times.

Depth of emplacement

The zone of shear fracturing postulated above was intruded by the first members of the intermediate group, while the remaining members of the intermediate group intruded steeper tension fractures more like the outer cone sheets. The original zone of shear fracturing was re-opened to allow intrusion of the late group but the geometry of the cylinder had changed by the intrusion of later members of the intermediate group. In order to project the zone of shear fracturing to the top of the assumed cylinder at the time of its formation the volume of the younger intrusives must be considered, and when this is done the top of the cylinder is calculated to have been 6-8 miles (9.5-13 km.) above the present level of erosion. This figure is for the ideal case but it does provide something on which to work.

Metamorphism of the intruded rocks at Mutton Bay is believed to have been at depths of 7-12 km., and the minimum thickness of sediments measured in the region, including the Wakeham series, is 10 miles (16 km.). There is a close correspondence between the possible depth of burial deduced from a study of the gneisses and that obtained by projection of the zone of shear fractures.

Studies in the Oslo region show that similar rocks intruded very near the surface. It is interesting to note that the Mutton Bay intrusion is old and granulite facies rocks and domical granite are exposed. The Nunarsuit intrusion of South Greenland intrudes low grade rocks and dips in the mass near the borders are shallow, suggesting that the zone of shear fractures is near the top edge of the postulated cylinder. The Ilimaussaq intrusion of South Greenland has shallow dips all the way to the borders and cuts low grade rocks, suggesting that erosion is near the roof of the pluton. The Kûngnât intrusive of South Greenland has shallow dips at the borders, intrudes amphibolite facies metamorphic rock, and is believed to be exposed just below the original roof.

A number of assumptions have been made above, but none are unreasonable. The mode and depth of emplacement fits the facts better than any other commonly found in the literature.

COMPARISON WITH OTHER AREAS

Saturated augite and fayalite-bearing syenites are well-known from numerous alkaline provinces of which the more important are New England, Oslo Fjord, South Greenland, the Kangerdlugssuaq region of East Greenland, Central Wisconsin, Nigeria, and Damaraland. In all these provinces nepheline syenite and gabbroic rocks are closely associated with the saturated syenites. Nepheline syenites are subordinate in Oslo Fjord, Nigeria, and New England, while granite is the most abundant in the latter two. Ring fractures are also a pronounced feature of the Nigerian and New England provinces. Faulting is closely associated with the plutonic rocks in the Oslo and South Greenland provinces.

The Oslo region might be considered the classic area and was made well-known by Brogger (1890, 1933). A series of studies on various aspects of the geology of the igneous rock complex was started in 1943, and much of this work is summarized by Oftedahl (1959) who was responsible for some of the studies. The systematic petrographic study of the plutonic rocks was done by Barth (1945) and many of his findings are frequently quoted. Characteristic of the Oslo region is the abundance of augite syenite. The area covered by the principal rock types is 8140 km^2 (Barth, 1945, p.17) which is considered an above-average sample of the rocks constituting the igneous province. Barth (1945) concluded from the frequency distribution curve of the Oslo plutonic rocks that the individual members may be attributed to crystallization differentiation of a syenite magma with granite occupying a position not cogenetic with the other plutonic rocks. Neither Barth nor Oftedahl believe the syenite magma could have been derived from the fractional crystallization of basalt as there is insufficient space in the crust. The magma is believed to have been formed from melting of the lower portion of the crust having the same composition, or by differential melting of a more basic rock.

A region that has been studied recently in some detail is the Gardar igneous province of South Greenland. A total area of 1501 km^2 (Watt, 1966) of plutonic rocks is exposed. Nepheline syenite is abundant but the frequency distribution curve with respect to SiO_2 is essentially like that of the Oslo region, with the granite again occupying an independent position and the gabbro of minor importance. Watt (1966) compared the rocks of the Gardar province of South Greenland to a number of other provinces and finds what he believes are important differences. These are differences in detail as might be expected but the general similarities are important.

The Mutton Bay intrusion might have a frequency distribution curve similar to that of the Oslo region except that the large amount of independent granite is lacking at Mutton Bay. The granite is believed to have formed at a higher level than that exposed now. It formed by assimilation of the country rock and it is suggested that the granites of the Oslo region and South Greenland have a similar origin. The least contaminated cone sheets at Mutton Bay are nordmarkites which are believed to be the parent magma and have a composition close to the peak of Barth's (1945) frequency curve.

Basic intrusions which have differentiated into saturated syenites should be mentioned. An excellent example of one of these, the Kiglapait layered intrusion on the Labrador coast, is described by Morse (1961). A larvikite has formed by extreme fractionation of a gabbro (alkali basalt?). Gillet (1956) describes closely associated syenites of alkali character with anorthosite in the Mealy Mountains. Within the present map area the giant gabbro dykes have given rise to an alkali syenite differentiate.

In the Province of Quebec an intrusion of the same age (Philpotts and Miller, 1964) and structural setting, and with a similar composition and size, is the Chatham Grenville stock about 50 miles northwest of Montreal. It is described by Osborne (1934). Late granites intruded by both stoping and pushing aside the country rock in contrast to early syenites that did not push aside the country rock. Osborne (1934a) compares the Chatham-Grenville stock to the nearby Rigaud Mountain described by Le Roy (1901). About 50 miles north-northwest of the Chatham-Grenville stock is the Loranger syenite stock which is structurally similar but varies in composition from skonkinite to syenite and is also described by Osborne (1935). In the same area Osborne (1935) described a poorly exposed alkaline syenite very much like that of Mutton Bay. He believes this syenite to be older than the Monteregian hills.

The Saguenay valley contains two syenites identical microscopically, in field appearance, and structural setting to the massive Mutton Bay syenite. These are the only two such syenites recognized by the author in an area of about 40,000 sq. miles, between Lake Mistassini and Trois Rivières, during 3 years association with the Grenville Project (Laurin, a, b and c in preparation). One poorly defined mass, the Lac-à-la-Croix syenite, lies on the break between the lowlands and highlands south of the village of Lac-à-la-Croix near Hebertville (Laurin, c in preparation ; Davies, 1967). The other mass, the Shipshaw syenite, outcropping on the main highway north of the Saguenay river opposite Arvida, was mapped by Osborne (1934b) and is being quarried as a building stone by National Granite Corp. Both intrusives are massive, coarse-grained, pink pyroxene syenites composed essentially of a hypersolvus single felspar exsolved to a microperthite. The Shipshaw syenite contains inclusions of anorthosite (Doig, personal communication), is cut by a porphyritic phase, and is apparently overlain by Trenton limestone.

Alkali complexes in the Ottawa graben at Meach Lake near Ottawa (Béland, 1951) and on Manitou Islands (Rowe, 1958) and Iron Islands in Lake Nipissing are believed pre-Ordovician.

It appears that the Ottawa and St.Lawrence valleys were the site of alkaline igneous activity in Precambrian to early Paleozoic time, possibly when the rift system, as recently postulated by Kumarapeli and Saull (1966), first developed. It is interesting that both the Mutton Bay and Chatham-Grenville intrusions occur where there is a change in direction of the sides of the rift so that they intruded weak zones at intersections of major faults. The two Saguenay syenites are also closely associated with major fractures.

Nordmarkite occurs in the Monteregian hills of Shefford and Brome and also in Mount Megantic, but in each case it is associated with gabbros and belongs to a Mesozoic period of intrusion.

The Mutton Bay syenite has similarities with syenites on the Labrador coast (Kranck, 1953 ; Cooper, 1951) and a dyke possibly related to these syenites has a late Precambrian age. If the Mutton Bay intrusion is to be placed in an igneous province it might very well be one including the syenites of the Labrador coast, and if continental drift is taken into account might also include the Gardar province of South Greenland. It is closer to the latter, assuming Bullard's (Girdler, 1965) assembly of continents, than to the Chatham-Grenville and the other intrusives of the Ottawa graben.

YOUNGER DYKES

The younger dykes are those believed younger than Precambrian, and include the giant gabbro dykes, the diabase and trachyte dykes that cut them, various lamprophyres, carbonate-rich dykes, and carbonate and quartz veins. The established relative ages of the younger dykes are given in Table XXI.

There is no reason to believe that the dykes cutting the giant gabbro have ages different to similar ones cutting the syenite. The Mutton Bay intrusion has its own suite of satellitic dykes which are confined to the pluton and have different characteristics to the younger dyke suite which are concentrated in the pluton only because it provided tension joints suitable for intrusion.

Giant gabbro dykes

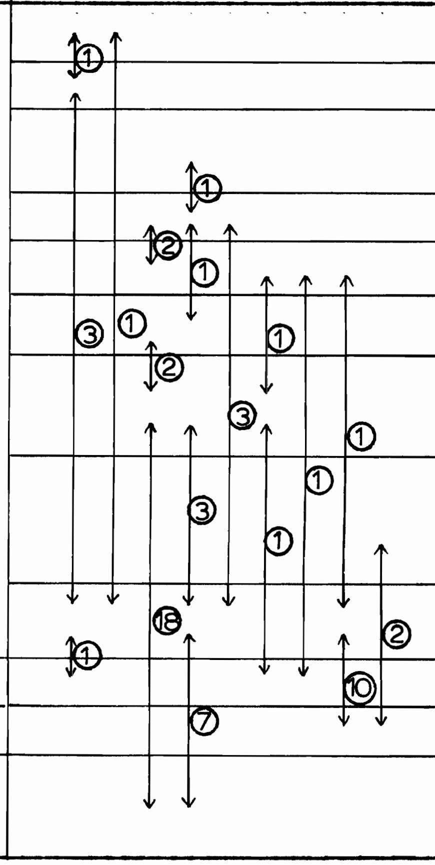
Coarse-grained vertical gabbro dykes of probable Ordovician age (470 m.y. Rb/Sr on biotite) strike 5-15° east of north. The largest dyke is exposed over 22 miles along the prominant linear valley including Dazé creek, St.Augustin river, Pagachou river, and Anse Tucker. This lineament can be traced northwards on topographic maps almost to the Labrador boundary. The smaller related dykes occur along disconnected fractures, and are exposed on the islands in Passage Mercier, west of Havre de l'Aigle, on the lake 1½-2 miles northwest of Lac Pagachou, and 3 miles north of the confluence of St.Augustin and St.Augustin-Northwest rivers.

The largest dyke is a negative topographic feature and nowhere were both contacts seen together, but airphotos suggest that it may be as much as 1/8 mile wide near the northern boundary of the St.Augustin area. The smaller dykes are positive topographic

Table XXI

Table of Formations for the Younger Dykes

		Pairs of dykes between which cutting relations were observed, and the number of times the relation was observed
Quartz veins		
Carbonate dykes		
Medium dark grey porphyritic trachyte		
Greyish red trachyte		
Pyroxene lamprophyres - ? - ? - ? - Olive grey trachyte		
Moderate reddish orange, dusky yellow brown and olive grey trachyte		
	Olive black to dusky yellowish brown trachyte	
Diabase	- ? - ? - Diabase	
Pale red trachyte		
	Giant gabbro	
Satellitic dykes of the Mutton Bay syenite intrusion		



Note : Dykes for which age relations were not established include

1) Biotite lamprophyres
2) Carbonatized dykes - probably related to carbonate dykes
3) Carbonate-rich felspathic dykes
4) Carbonate dyke containing biotite - cut by, and possibly unrelated to the normal carbonate dykes
5) Miscellaneous trachytes

features 125-200 feet wide. The dyke west of Havre de l'Aigle gives way in one place to a swarm of finer-grained dykes, and on crossing Petit Rigolet it is offset about 1/8 mile to the left by what is believed to be post-dyke faulting. Both larger and smaller dykes are cut by numerous diabase dykes. Several olive black to dusky yellowish brown trachytic dykes were observed cutting the larger dyke in Anse Tucker (fig.149, p.293).

Composition of the larger dyke is extremely variable, ranging from gabbro to syenite. The gabbroic phase is exposed on St.Augustin and Pagachou rivers, while exposures along Dazé creek are essentially syenites. Syenite boulders also occur on Île aux Graines east of Passage Fournier, the extension of the lineament to the south of Anse Tucker.

Rocks intermediate between the gabbro and the syenite, in which a pink syenitic fraction lies interstitial to a grey or green gabbroic fraction, are common. On St.Augustin river syenite occurs in gabbro as irregular veins and patches with gradational contacts. It appears that in some cases residual syenitic liquid crystallized between the plagioclase laths and in others segregated to form syenite masses.

Petrology of the gabbroic phase of the larger dyke : The gabbroic phase is generally coarse-grained with felspar laths 5-10 mm. long, but it is medium- to coarse-grained near the contacts. It is light grey to light olive grey with a typical diabasic to sub-diabasic texture. The rock is essentially an anorthositic gabbro consisting of labradorite, augite, biotite, with lesser amounts of brown hornblende, opaque minerals, and apatite, and in some cases sphene. Chlorite, actinolite, opaques, and serpentine are late magmatic or deuteric minerals. A modal analysis of a typical specimen is given in table XXII.

Labradorite is slightly altered to sericite and occurs as anhedral to subhedral laths, some of which are zoned and have andesine rims. As much as 17 percent range in anorthite content was measured in single crystals.

Euhedral apatite, followed by anhedral to subhedral opaque minerals, crystallized early. Anhedral to subhedral augite is interstitial to or included in the rims of plagioclase crystals and appears to have started crystallizing after the cores of the plagioclase crystals. A brown amphibole is a minor constituent that crystallized after the pyroxene. Strongly pleochroic biotite encloses the earlier minerals and occurs in fairly large anhedral flakes that appear to be primary.

Green alteration products are after the ferromagnesian minerals, including perhaps olivine.

Petrology of the syenite phase of the larger dyke : The syenite phase is essentially moderate orange pink to pale reddish brown, has the same texture, and grades into the gabbro with rocks of intermediate composition common. Microscopically the syenite consists of microperthite (occasional plagioclase laths), amphibole, augite, and magnetite, with apatite and zircon as accessories. Quartz is present in some sections. Actinolite, chlorite, biotite, sphene, and carbonate are late magmatic and deuteric minerals. A modal analysis of a typical specimen is given in table XXII.

Anhedral to subhedral magnetite crystallized early and commonly encloses euhedral apatite which is not as abundant as in the gabbro.

Table XXII

Modal analyses of a typical specimen of anorthositic gabbro and its syenitic differentiate

	Anorthositic Gabbro	Syenite
Plagioclase felspar	68.2	-
Alkali felspar	-	87.1
Quartz	-	1.8
Augite	5.2	0.7
Hornblende	Tr.	2.4
Biotite	6.9	0.1
Opaques	5.4	1.6
Apatite	1.9	0.1
Sphene	Tr.	0.1
Zircon	-	0.2
Carbonate	-	-
Green alteration minerals	12.4	5.9
Total	100.0	100.0

Modal analyses on single thin sections counting 1000 - 2000 points

Sphene is closely associated. Anhedral to subhedral augite, together with the magnetite, is enclosed in perthite, while green to brown anhedral hornblende, which is the dominant ferromagnesian mineral, occurs interstitial to the felspar. Biotite occurs as small flakes rimming magnetite.

The microperthite is strongly clouded, occurring as stubby subhedral crystals. Scattered throughout the rock, and surrounded by perthite, are long laths of well-twinned plagioclase (An_{28-32}). A partial analysis of the bulk felspar with calculated felspar molecules is given in table XXIII. Quartz occurs interstitial to the felspar and is cracked but not strained.

Green alteration minerals, in some cases with magnetite, are after the ferromagnesians, mostly pyroxene and perhaps olivine.

Table XXIII
Partial chemical analysis of bulk felspar and calculated felspar molecules of syenite phase of a giant gabbro dyke

Na_2O	K_2O	CaO	CO_2	Ab	Or	An	Dolomite	Total
6.43	6.80	0.92	0.19	54.36	40.17	3.97	0.40	98.90

Diabase dykes

Diabase dykes are abundant, cutting the giant gabbro dykes, the Mutton Bay syenite, and the country rock adjacent to these intrusives. Hale (1962) mentions the surprising scarcity of diabase dykes in the interior region, and points out that those observed by him in Robertson Lake and Inner Rigolet are confined to an area where prominant northeast-trending faults are obvious. It should be stressed that it is where the faults intersect young igneous masses that diabase and trachytic dykes are concentrated.

The diabase dykes are all olive black, fine-grained rocks with very fine-grained chill contacts. Some of the dykes are amygdaloidal, others porphyritic, and jointing is typically perpendicular to contacts.

Microscopic features : The rocks are all fine-grained with diabasic to sub-diabasic texture. They are composed essentially of plagioclase with pyroxene or amphibole together with biotite, opaque minerals (including pyrite), and apatite. Chlorite is a late-deuteric alteration mineral.

Subhedral apatite is early and is enclosed in plagioclase. Black opaque minerals occur in the pyroxene diabase as small rounded subhedral grains and in the amphibole diabase as irregular anhedral grains resulting from alteration. Amphibole, strongly pleochroic in greens and enclosing black opaque minerals, occurs in amphibole diabases, both in the matrix and as anhedral phenocrysts or clusters of phenocrysts, while in pyroxene diabases it appears to be a late alteration mineral. Biotite is an alteration after amphibole and occurs as ragged flakes in the amphibole diabases. In the pyroxene diabases it occurs as anhedral poikilitic flakes enclosing black opaque minerals, that appear to have grown at a late stage at the expense of pyroxene and amphibole.

The anhedral to rarely subhedral plagioclase laths are well-twinned and zoned. In a pyroxene diabase they are fresh labradorite with an average core composition of An_{55}, and in an amphibole diabase are clouded with a core composition of An_{37}. Their borders contain small inclusions of pyroxene and opaque minerals, showing that plagioclase crystallized first.

Chlorite is a late alteration mineral occurring as pseudomorphs probably after pyroxene.

Trachyte dykes

Trachyte dykes are of more than one age and differ in colour and composition. The dykes in the table of formations are dykes whose age relations are known, but many trachyte dykes cannot be fitted into this table.

Trachyte dykes are fine-grained and many contain phenocrysts and/or xenocrysts (fig.102). The proportion of phenocrysts or xenocrysts to groundmass is variable, and in rare dykes xenocrysts constitute over 50 percent of the rock (fig.106, p.231).

Colour varies from moderate reddish orange through pale red and brownish grey to olive grey. Contacts are usually darker greys and browns and are finer-grained than the cores of the dykes. The dykes are generally trachytoidal (fig.103) particularly near the contacts.

Trachyte dykes are concentrated in, though not confined to the Mutton Bay intrusion which is believed to have had a better developed fracture system than the gneisses. The early relatively fluid diabases intruded fractures in both pluton and gneisses but only the pluton provided numerous and large enough openings for intrusion of the probably more viscous trachytes.

The dykes are felspathic and contain alkali felspar that is

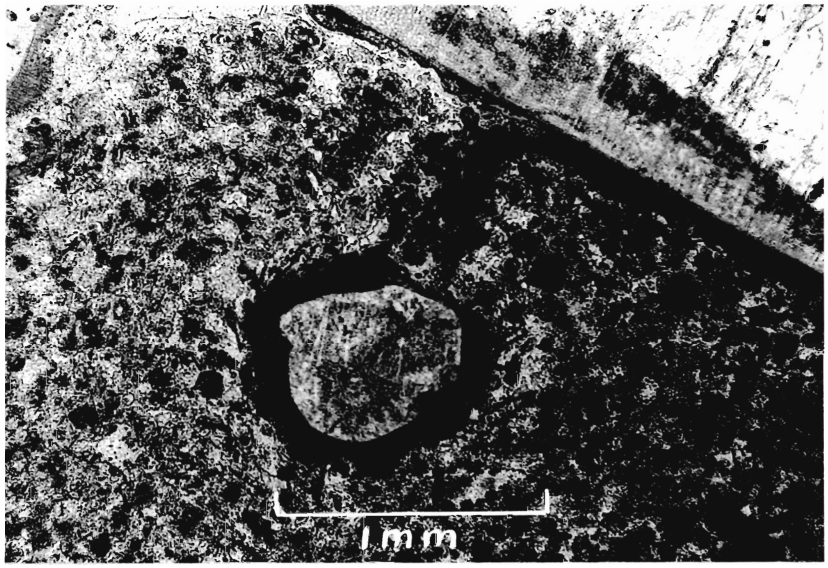


Fig. 102 - Felspar xenocrysts in a fine-grained dark greenish grey contact zone of an olive grey trachyte dyke showing melting and alteration at the edges of xenocrysts. Crossed nicols. X 35.

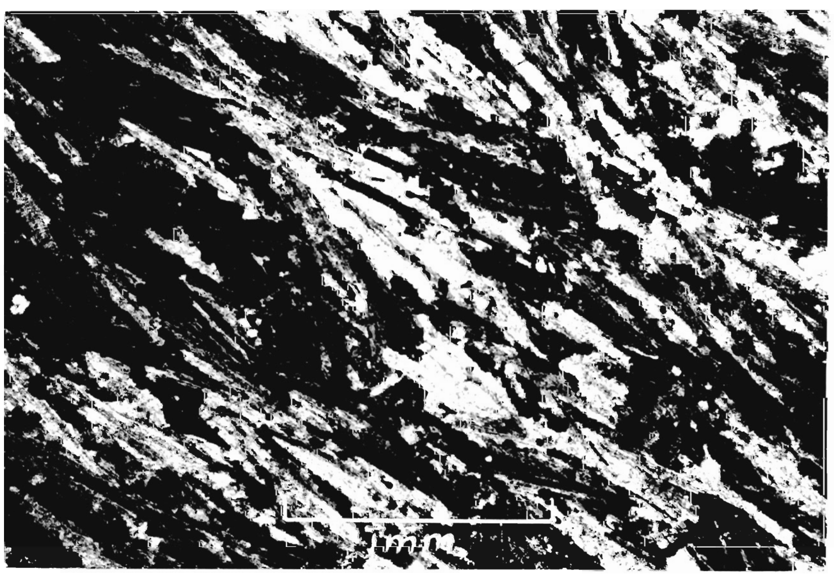


Fig. 103 - Well foliated trachyte. Crossed nicols. X 35.

cloudy with a light brown colour. The cloudiness makes optical work difficult but indices of refraction are low, twinning is simple, and phenocrysts or xenocrysts have $2V_x = 44\text{–}86^\circ$. Plagioclase xenocrysts occur in brown dykes cutting the giant gabbro. Quartz is commonly present in minor amounts and is clear, lying interstitial to the felspar. Carbonate is invariably present and is fairly abundant (up to 10 percent) in the brown varieties, and appears to be a late crystallizing primary mineral.

Ferromagnesian minerals occur in variable quantities but are most abundant in the brown varieties. These include : amphiboles, pleochroic in green and brown, strongly pleochroic brown biotite, chlorite, and opaque minerals. Apatite is a common accessory mineral, occurring as small euhedral prisms. Some specimens contain fluorite and sericite is a common alteration mineral.

<u>Biotite lamprophyres</u>

A rare biotite lamprophyre contains pyroxene and biotite phenocrysts in a groundmass of felspar, pyroxene, biotite, opaque minerals, and apatite. Chlorite and serpentine occur in masses pseudomorphous after some phenocrysts.

<u>Pyroxene lamprophyres</u>

Pyroxene lamprophyres are rare dykes but are conspicuous. They are fine-grained, olive black, and have large augite phenocrysts and pink felspar 'xenocrysts' concentrated in their centres.

The augite phenocrysts are brown and zoned in thin section and one phenocryst studied has a rim with $2V_z = 46^\circ$ and a core with

$2V_z = 40^{\circ}$. The phenocrysts are euhedral to subhedral and from 0.3–20 mm. in diameter with the larger phenocrysts enclosing smaller ones in addition to black opaque minerals. Chlorite and opaque minerals are alteration products of the augite. Biotite occurs in the fine-grained undetermined groundmass and carbonate is present in minor amounts.

Carbonate veins and dykes

Fine-grained greenish grey veins and dykes which weather greyish orange occur throughout the area and are conspicuous in the syenite pluton. They are generally 1/2 to 2 inches wide and fill fractures. Many contain abundant inclusions, some of which have been transported and do not match the wall rock. They exhibit flow features such as scouring, flow differentiation (fig.104), and bending of enclosed mica flakes (fig.105). Some inclusions are broken up by injection of carbonate along grain boundaries. The above features suggest flow of a solid-liquid mush.

The carbonate is essentially a granular dolomite with grains 0.025 mm. in diameter. A rare vein, cut by the normal ones, contains quartz and a coarser grained white-weathering calcite with small books of black biotite (2-4 mm. in diameter) along its contacts. Bailey (1964) investigated the equation orthoclase + dolomite + H_2O = phlogopite + calcite + CO_2 and found that the reaction goes from left to right at 300°C at low CO_2 pressures, and 600°C at high CO_2 pressures. The rare occurrence of this reaction suggests temperatures of crystallization of the dolomite at least below 600°C. The biotite and calcite-bearing vein probably crystallized

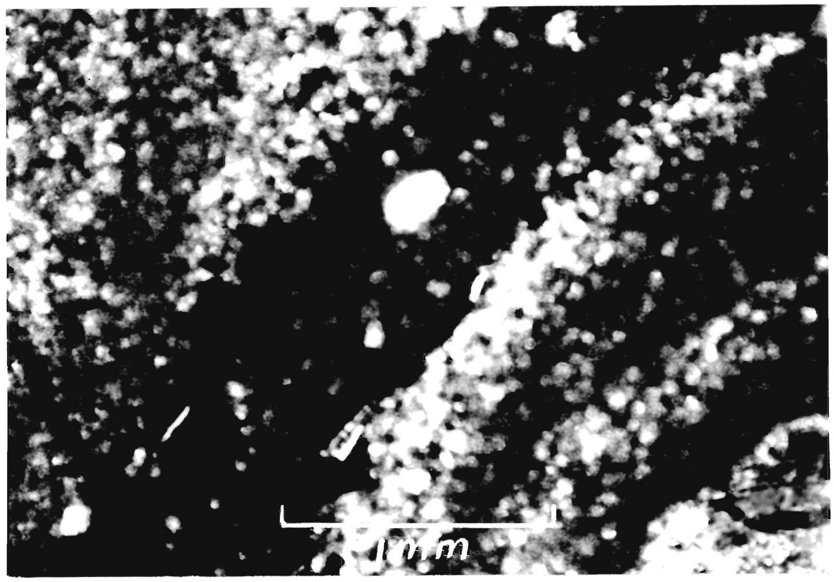


Fig. 104 - Fine-grained carbonatite dyke showing the effect of flow differentiation. Fine material is dark and coarse material light. Repeated pulses of magma have caused repetition of sequence from fine-grained to coarse-grained towards the dark and last intrusion in the centre of photo. Plain light. X 35.

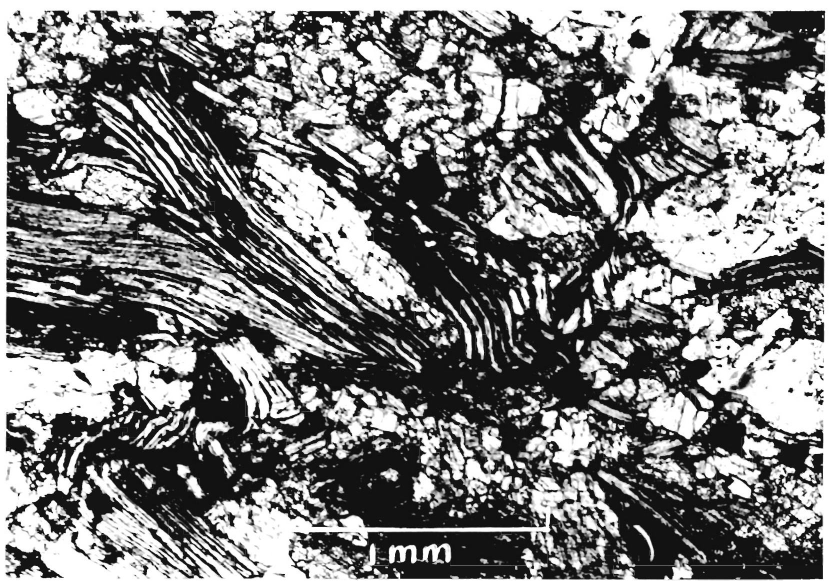


Fig. 105 - Carbonatite dyke containing biotite from an assimilated inclusion. The flakes are bent suggesting plastic flow in the dyke rather than deposition from a solution. Plain light. X 35.

at a higher temperature or at a lower CO_2 pressure than the normal dolomite veins. It may be very much older and possibly related to the Mutton Bay intrusion. The isotopic composition of carbon and oxygen in the carbonate minerals of an exceptionally large dyke (4 feet wide) has been determined by Gold and Gerencher (1967) who state that "two types of carbon are present ; probably a late atmospheric (light) and an early plutonic (?)".

Of economic interest are veins in the gneisses about 1/2 mile north of the syenite-gneiss contact at Île Fecteau. They are exposed in an area 30 x 10 feet, are up to 2 inches wide, and in addition to dolomite contain coarse white to pink calcite and galena. Galena occurs also in a small fracture on Île Fecteau. These showings indicate the presence of mineralizing solutions that are probably post-Early Paleozoic and there is every reason to expect ore deposition in favourable host rocks in the area.

Similar carbonate dykes, up to 18 inches wide, were recognized and mapped by the author in an area between Kenogami and Chicoutimi in the Saguenay valley (Davies, 1967 ; Laurin, c in preparation). There are essentially two varieties, a fairly pure orange-weathering variety, and a green variety which generally contains biotite, iron oxides, and fragments of country rock. Younger galena- and pyrite-bearing calcite veins are closely associated. The dykes, which are apparently pre-Trenton limestone, partially surround, dip in towards, and cut an alkali syenite like that of Mutton Bay. As for most of the young dykes at Mutton Bay the syenite may simply be a structurally favourable centre for intrusion, but it strongly suggests a relation between the dykes and the syenite.

Carbonatized dykes

At the bottom of Baie des Ha! Ha! are two strongly altered porphyritic dykes that have been brecciated, altered to carbonate, chlorite, muscovite, and opaque minerals, and cemented by late dolomite.

A partial analysis of one of the dykes (20.56% CO_2 ; 10.65% CaO) gives a calculated dolomite content of 43.07 percent. The country rock is strongly fractured possibly by the explosive nature of the carbonate liquid, but the fracturing is more likely related to the Petit Rigolet fault.

Near Mutton Bay is a basic lamprophyre dyke containing altered phenocrysts pseudomorphous after pyroxene and olivine in a chloritic groundmass. Some phenocrysts are altered to carbonate and chlorite and others to carbonate and black opaque minerals. The dyke was not brecciated like those in Baie des Ha! Ha!

Carbonate-rich felspathic dykes

Three carbonate-rich felspathic dykes provide some clues concerning the relation between various carbonate-bearing dykes.

The first dyke is 2 inches wide and consists essentially of thin perthite plates up to 10 mm. long, aligned parallel to the dyke contacts (fig.106). Many of the felspar plates are fractured and were derived from the country rock, with minor amounts of apatite, sphene, and opaque minerals. Material interstitial to the felspar amounts to 10 percent and consists of carbonate and quartz with minor amounts of fluorite. Carbonate, entering a strongly sheared or close-jointed zone in syenite, is believed to have acted as a lubricant

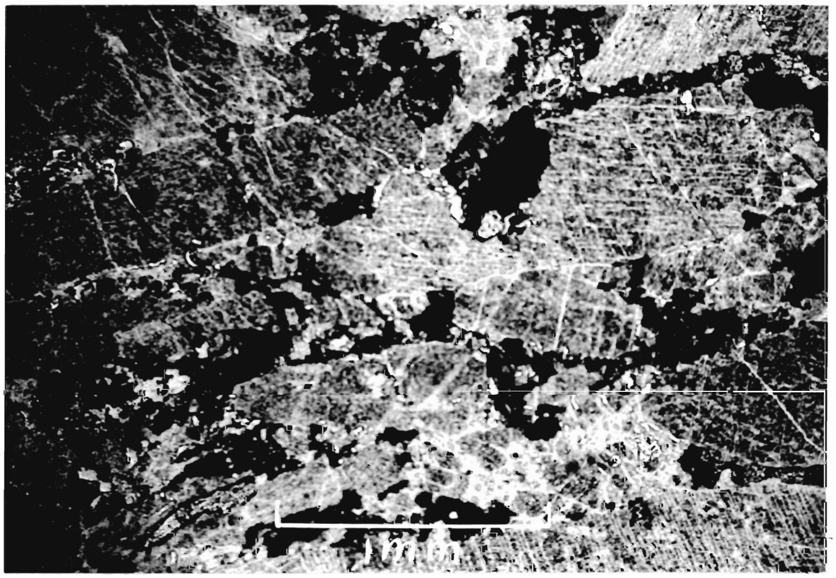


Fig. 106 - 2-inch wide dyke composed essentially of microperthite xenocrysts with about 10 percent interstitial material, including carbonate, quartz, and minor fluorite.
Plain light. X 35.

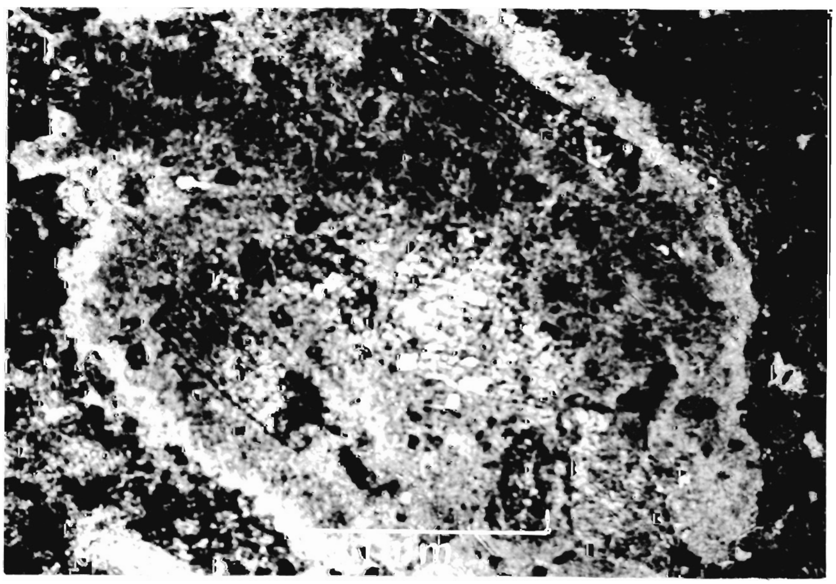


Fig. 107 - Remnants of perthite in a mixture of carbonate and finely matted fibrous greyish orange mineral.
Plain light. X 35.

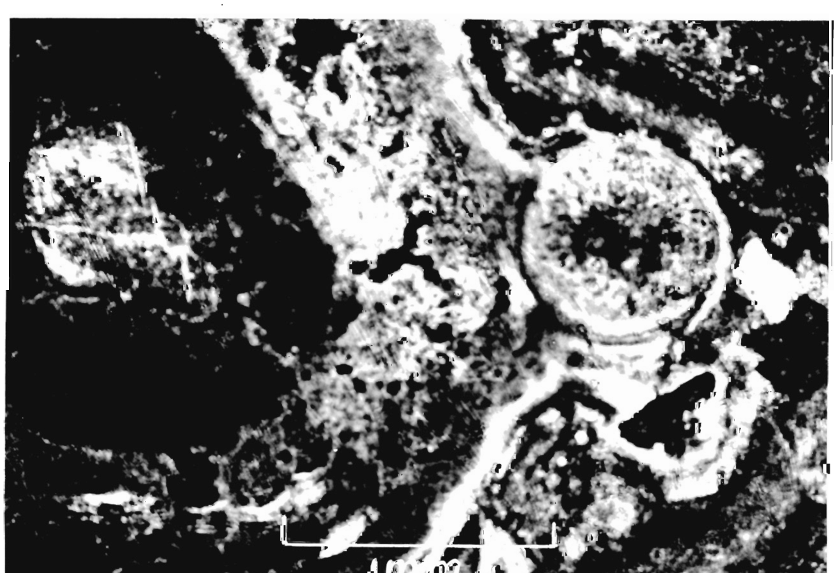


Fig.108 - Light brown globular masses of a fibrous mineral, the larger surrounding a remnant of felspar. Carbonate occurs in the globule but is rich interstitial to the globules
Plain light. X 35.

which permitted movement or flow of the felspar crystals.

The second dyke is similar to the first with felspar fragments, some of which are bent , lying in a matrix of carbonate and opaques. Brown material, composed of matted sperulitic matter containing grains of carbonate, surrounds corroded felspar crystals and appears as if it may have been a melt (fig.107, p.231).

The third dyke consists almost entirely of brown globular masses, several of which contain a small corroded core of felspar (fig.108, p.231). The globules are very rounded and coalesce but appear to have formed around separate centres. Carbonate occurs concentrically around the centres of the globules, and the matrix interstitial to the globules is very carbonate-rich. This dyke is a clear case of melting of the felspar by a carbonate-rich melt.

The three dykes described represent stages in the development of carbonatized felspathic dykes. This probably applies to the basic dykes as well. Carbonate-rich material enters fractures, altering, and, in some cases, melting the country rock. To be able to melt perthite a temperature of 695°C at 5000 bars water pressure (Yoder, Stewart, and Smith, 1957) must have been reached.

Quartz veins

Narrow quartz veins filling joints and fractures represent the last phase of igneous activity. The quartz occurs in euhedral to anhedral crystals sometimes accompanied by purple fluorite. Quartz veins cut carbonate veins but, in some carbonate veins, quartz is an essential constituent. Quartz, filling fractures in shear zones in syenite, replaces ferromagnesian minerals. In green pyroxene-plagioclase gneiss quartz veins are accompanied by epidote. The SiO_2-rich hyrdothermal solutions altered the ferromagnesian minerals of the wall rock to chlorite and black ore minerals, and plagioclase to chlorite and epidote. Epidote is concentrated in the veins along the contact and in inclusions of country rock, as well as being disseminated in the wall rock. The greatest macroscopic effect is the clouding of the felspars, especially the potash felspar, and their change of colour to a light brown. Haematite occurs as alteration rims around magnetite cubes. Apatite and zircon are unaffected. A 2-inch wide quartz vein cutting the syenite contact south of Mutton Bay carries a little pyrrhotite.

Chemistry of the trachyte dykes

The fine grain size of the trachyte dykes makes identification of minerals and determination of felspar composition difficult and modal analyses unreliable. The rocks are essentially felspathic and any marked differences among them can be expected to be reflected in the felspar composition. Sodium and potassium in the trachyte dykes are essentially confined to albite and potash felspar respectively, but calcium occurs both in the anorthite molecule of the felspars and in carbonate which is abundant in the dykes. If the composition of the carbonate is known, analyses for Na_2O, K_2O, CaO and CO_2 permit the calculation of the percentage felspar molecules.

Partial analyses were made on samples from 11 dykes whose relative ages are known and which correspond to 6 groups. In 5 of the dykes there is insufficient CaO to combine with all the CO_2 present to form calcite, but there is sufficient to form dolomite. On the assumption that the carbonate in the dykes is dolomite the felspar molecules are calculated and are given in table XXIV. The amount by which the total felspar plus dolomite falls short of 100 percent is the amount of quartz and ferro-magnesian minerals in the rocks.

If the calculated minerals are plotted against the relative age of the dykes a systematic variation is shown by anorthite and dolomite (figs.109 and 110). A break between the second and third groups indicates that there may be two series of dykes, each increasing in carbonate and decreasing in anorthite content. It also suggests that the diabase may belong between the second and third groups, and, since red dykes cut diabase, it is possible that there are either two series of diabases and/or two series of red trachytes, with the second diabase at the beginning of the first series, and the second red trachyte at the end of the second series.

Felspar molecules recalculated to 100 percent are plotted on a triangular diagram (fig.111). The two early groups are low in anorthite and plot near the albite-orthoclase eutectic (60 Ab, 40 Or). The third group is calcic and at least one of the two samples (No.6) must contain free plagioclase. The fourth and fifth groups are lower in anorthite and, except for the extreme potassic dyke, plot near the eutectic. The sixth group is very calcic and belongs perhaps to a third series of dykes. Two samples that are high in orthoclase should be termed potassic. The potassic-rich dykes are also those high in CO_2.

In the Mountain Pass district of California (Olsen et al, 1954) the carbonatites are believed to have been derived as a residual from

Table XXIV

Partial Analyses of Trachyte Dykes of the Mutton Bay Area

Chemical Analysis (weight percent)

	Na_2O	K_2O	CaO	CO_2
1.	4.42	7.41	2.21	3.38
2.	5.99	6.52	1.38	1.19
3.	6.33	6.30	1.07	1.60
4.	4.66	6.08	2.55	4.68
5.	5.42	5.64	2.69	0.22
6.	3.70	6.32	6.23	1.15
7.	6.29	4.67	1.80	2.49
8.	6.16	6.11	2.19	0.51
9.	3.50	9.07	2.76	3.65
10.	5.76	6.41	2.47	1.69
11.	4.10	3.19	7.03	2.16

Calculated Mineral Components (weight percent)

	CaO in $CaMg(CO_3)_2$	CaO left	Dolomite $CaMg(CO_3)_2$	Ab	Or	An	Total Felspar
1.	2.15	0.06	7.08	37.36	43.75	0.30	81.41
2.	0.76	0.62	2.49	50.65	38.51	3.08	92.24
3.	1.01	0.06	3.35	53.51	37.20	0.30	91.01
4.	2.98	-	9.80	39.37	35.92	-	75.29
5.	0.14	2.55	0.46	45.80	33.34	12.66	91.80
6.	0.73	5.50	2.41	31.27	37.34	27.30	95.91
7.	1.58	0.22	5.22	53.18	27.58	1.09	81.85
8.	0.32	1.87	1.07	52.02	36.07	5.86	93.95
9.	2.32	0.44	7.65	29.55	53.57	2.18	85.30
10.	1.07	1.40	3.54	48.68	37.87	6.95	93.50
11.	1.37	5.66	4.53	34.69	18.87	28.09	81.65

Felspars Recalculated to 100 percent

	Ab	Or	An	Total
1.	45.8	53.8	0.4	100.0
2.	54.9	41.8	3.3	100.0
3.	58.9	40.8	0.3	100.0
4.	52.0	48.0	0.0	100.0
5.	49.9	36.3	13.8	100.0
6.	32.7	38.9	28.4	100.0
7.	64.9	33.8	1.3	100.0
8.	55.4	38.4	6.2	100.0
9.	34.7	62.8	2.5	100.0
10.	52.1	40.5	7.4	100.0
11.	42.5	23.1	34.4	100.0

Field numbers of samples analysed : 1. (RD-31-27) ; 2. (RD-55-44) ; 3. (RD-4-18) ; 4. (R-26-8) ; 5. (RD-31-26) ; 6. (L-5-2) ; 7. (Y-36-2) ; 8. (RD-1-27) ; 9. (RD-1-26) ; 10. (L-14-2) ; 11. (RD-61-26)

Analyst : R.Davies, 1966

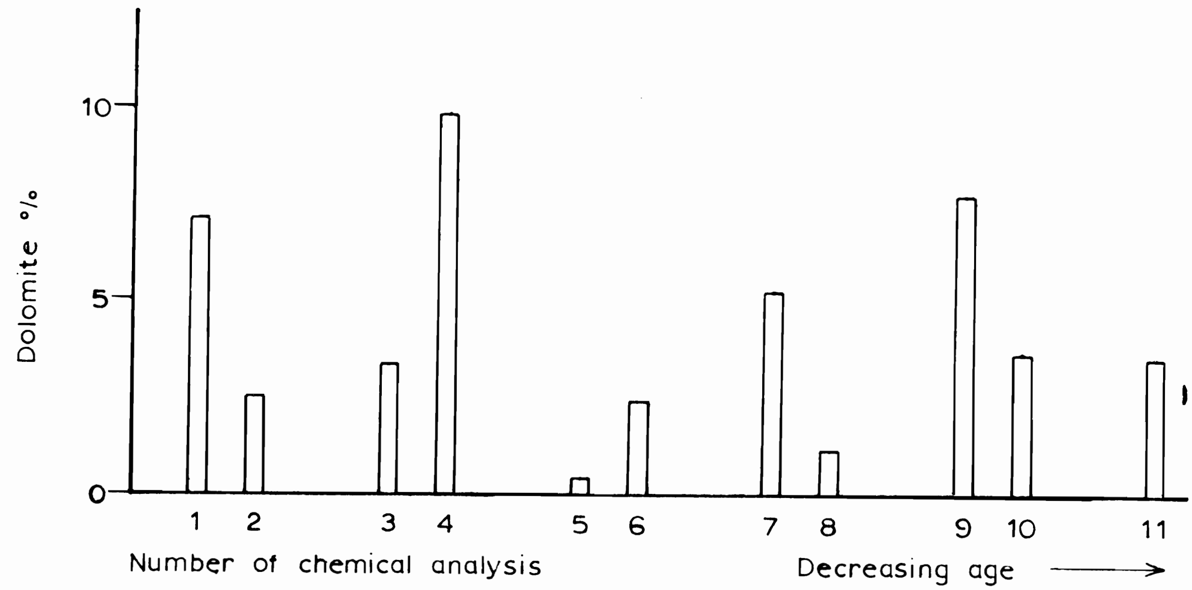


Fig. 109 - Percent dolomite in younger felspathic dykes arranged according to their relative age. Group 1 (1,2) - pale red trachyte ; Group 2 (3,4) - moderate reddish orange trachyte ; Group 3 (5,6) - dusky yellow brown trachyte ; Group 4 (7,8) - olive grey trachyte ; Group 5 (9,10) - greyish red trachyte ; Group 6 (11) - medium dark grey porphyritic trachyte.

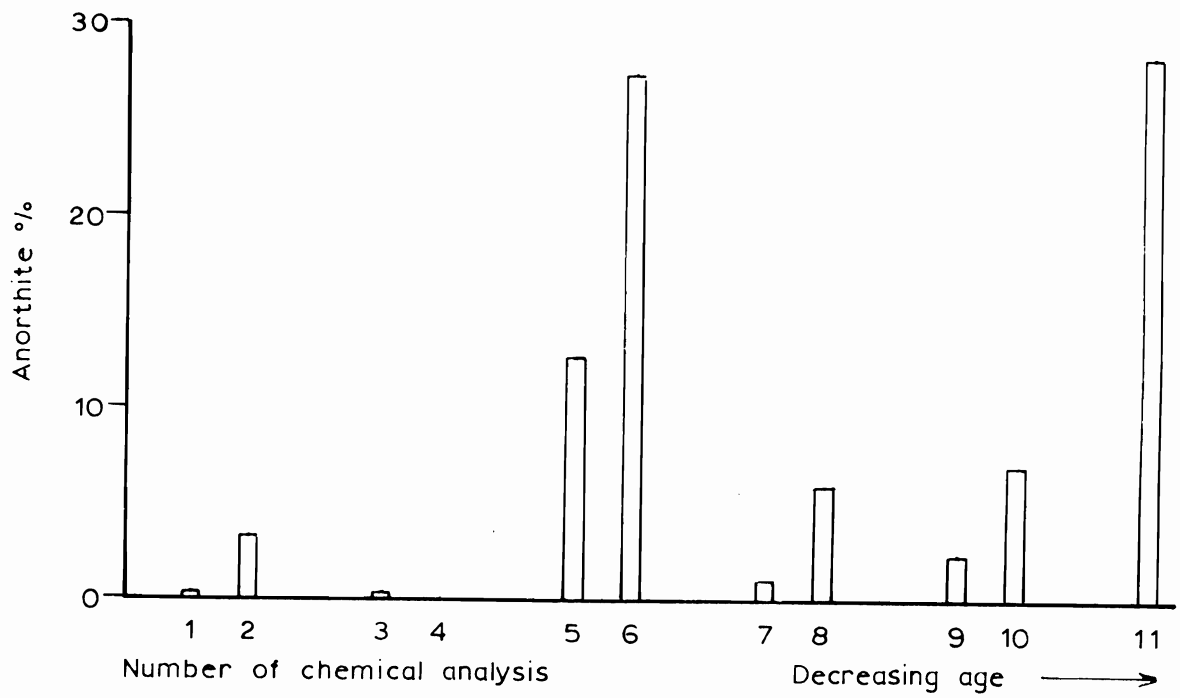


Fig. 110 - Percent anorthite in younger felspathic dykes arranged according to their relative age. Group 1 (1,2) - pale red trachyte ; Group 2 (3,4) - moderate reddish orange trachyte ; Group 3 (5,6) - dusky yellow brown trachyte ; Group 4 (7,8) - olive grey trachyte ; Group 5 (9,10) - greyish red trachyte ; Group 6 (11) - medium dark grey porphyritic trachyte.

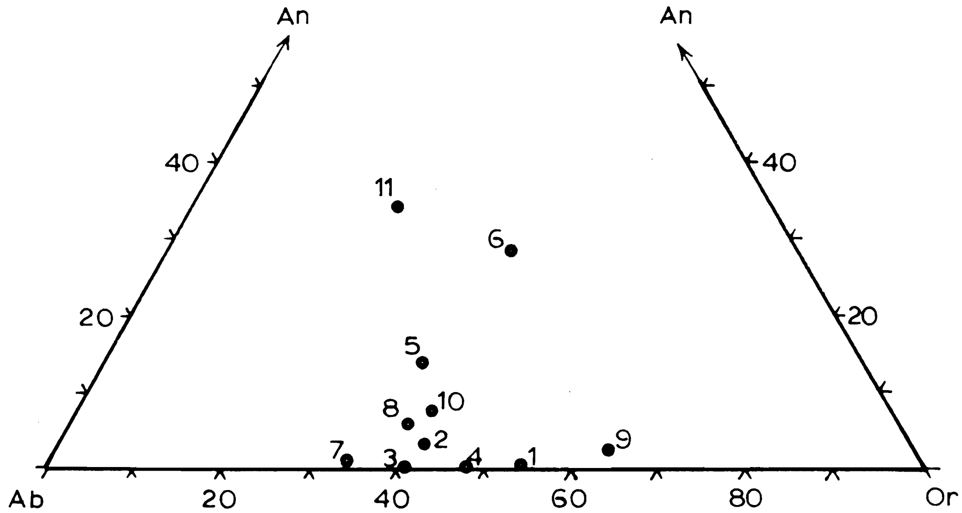


Fig. 111 - Felspar composition of the younger trachyte dykes calculated from Na_2O, K_2O, CaO and CO_2 analyses of the whole rock, and plotted in terms of weight percent Or, Ab, and An. Group 1 (1,2) - pale red trachyte ; Group 2 (3,4) - moderate reddish orange trachyte ; Group 3 (5,6) - dusky yellow brown trachyte ; Group 4 (7,8) - olive grey trachyte ; Group 5 (9,10) - greyish red trachyte ; Group 6 (11) - medium dark grey porphyritic trachyte.

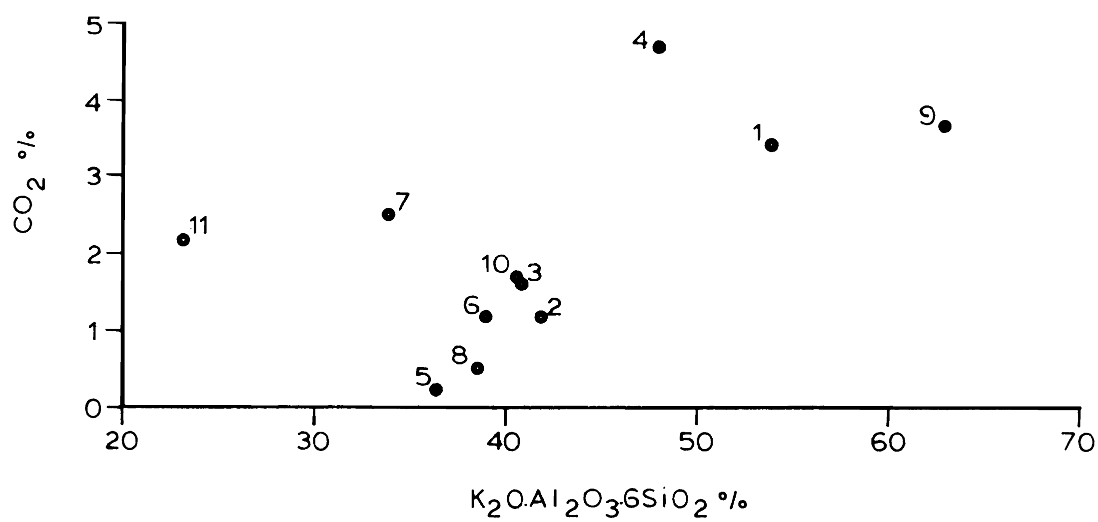


Fig. 112 - CO_2 percent (analysed) plotted against orthoclase percent (calculated from K_2O analysis of whole rock). Group 1 (1,2) - pale red trachyte ; Group 2 (3,4) - moderate reddish orange trachyte ; Group 3 (5,6) - dusky yellow brown trachyte ; Group 4 (7,8) - olive grey trachyte ; Group 5 (9,10) - greyish red trachyte ; Group 6 (11) - medium dark grey porphyritic trachyte.

potash-rich magmas from which potash-syenites and granites earlier crystallized. King (1965) suggests that carbonatites initially contain alkali carbonates and ascribes the accompanying alkali metasomatism of carbonatites to the 'fugitive' (alkali) constituents. Von Ekerman (1961) believes the carbonate cone sheets of Alnö are the result of a magmatic fluid of mainly potash carbonate which reacted with the wall rock, absorbing silica and soda in exchange for potash.

In the trachyte dykes CO_2 increases with potash felspar as shown in fig.112 which is in accord with the residual carbonate-rich liquid being potassic. The K_2O, SiO_2, CO_2 concentrated in the residual liquid is believed to react with $CaAl_2Si_2O_8$ and the ferromagnesians to form $(CaMg)CO_3 + K_2Al_2Si_6O_{16}$. Tomkeieff (1961) postulated that Na_2CO_3 within a magma reacts with 'shadow mineral molecules' to produce reactions of the type anorthite + Na_2CO_3 = nepheline + $CaCO_3$. This was actually found by Koster von Groos and Wyllie (1963) in the system 80Ab20An - Na_2CO_3 - H_2O (at 1 Kb and around 750°C). Their work on the systems Ab - Na_2CO_3 - H_2O and 80Ab20An - Na_2CO_3 - H_2O (at 1 Kb and around 750°C) is of interest in that it reveals an immiscibility gap between alkali carbonate magma and silicate magma. Thus the alkali carbonate can concentrate independently of the silicates until the temperature of crystallization of alkali felspar and alkali carbonate is reached. At this point the felspar composition is fixed according to its position on the differentiation trend curve. Any reaction with the silicates now to form calcite or dolomite will result in abnormal amounts of one or other or both alkali felspars.

Excess K_2O or Na_2O will be drawn into the country rock and this might account for the red alteration adjacent to so many trachyte dykes in the gneisses of the area. The carbonatite dykes and veins probably represent carbonate that was tapped off from the trachyte dykes.

Relationship of younger dykes to the Mutton Bay intrusion

The younger dykes have not been studied in detail because they are not directly related to the Mutton Bay sequence of intrusions, and in addition are much younger. However, their magma originated in the same area of the crust as the magma of the Mutton Bay intrusion and alkali syenite is common to both intrusive periods.

The younger dykes form a complete sequence from gabbro to alkali syenite (with up to 10 percent carbonate and minor quartz) and finally to carbonatite. Carbonate is a late-crystallizing mineral of the Mutton Bay syenite and it is possible that some of the carbonate dykes are related to it. However, a carbonate differentiate that may have formed from the syenite probably formed at a high level within or above the intrusion and has been removed by erosion. The close spacial relation between carbonatite dykes and alkali syenite in the Saguenay Valley supports the hypothesis of a close genetic relation between the two rocks, and it is possible that the Saguenay syenite is exposed near its roof.

If a parallel does exist between the younger dykes and the Mutton Bay intrusion, the evidence provided by the giant dyke suggests that the parent magma of the syenite was more basic than the nordmarkite, as suggested on p.214, and has a composition near the average of that of the giant dyke. Early basic lamprophyres indicate the presence of a basic magma at the time of the Mutton Bay intrusion. The actual average composition of the giant dyke, and therefore of its parent magma, can only be guessed and no attempt will be made to do so. The parent magma of the Mutton Bay rocks is still considered a nordmarkite but one that was completely separated from its parental magma which was probably more basic.

PALEOZOIC SEDIMENTS

The only consolidated unmetamorphosed sediments are narrow sandstone dykes (fig.113) found at several points in the Mutton Bay area. They are 1/16 - 1 1/8 inches wide, branch, and contain inclusions of country rock. They are found in syenite and porphyritic granite and they are undoubtedly more noticeable in these relatively homogeneous rocks than in the gneissic rocks.

The dykes are essentially quartz-cemented sandstones, yellowish grey in colour, sugary, and medium-grained. They are orthoquartzites composed of 95 percent subrounded quartz grains (fig.114) which show a secondary overgrowth with the original outline preserved by minute inclusions. Microcline constitutes about 5 percent of the rock and displays a rim of more altered material which may be a secondary overgrowth.

Contacts with the country rock are sharp and quartz grains pressed into the wall rock plagioclase of the porphyritic granite resulted in crushing, solution and redeposition, and bending of twin lamellae (fig.115). This probably occurred after burial.

The rock was consolidated by Pleistocene times as the dykes are polished by glacial action. Fracture cleavages at angles of 30° to the contacts are sometimes present, indicating movement after consolidation.

Similar sandstone dykes are found west of the area at Mingan where they are correlated with the 'Potsdam sandstone' or the Ordovician (Longley, 1950). The lower sandstone beds at Blanc Sablon

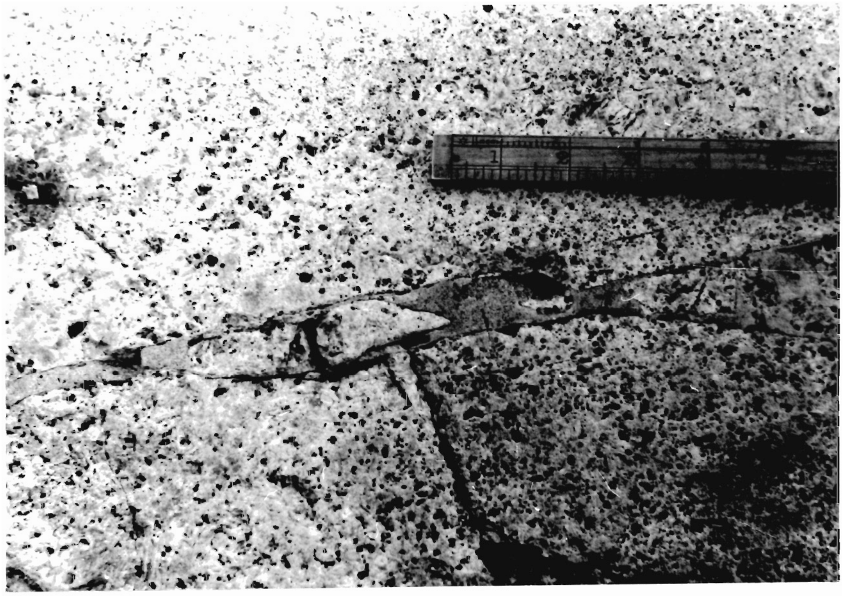


Fig. 113 - Sandstone dyke at Tabatière filling fracture in coarse-grained massive green syenite . Photograph shows branching of the dyke around an inclusion of country rock.

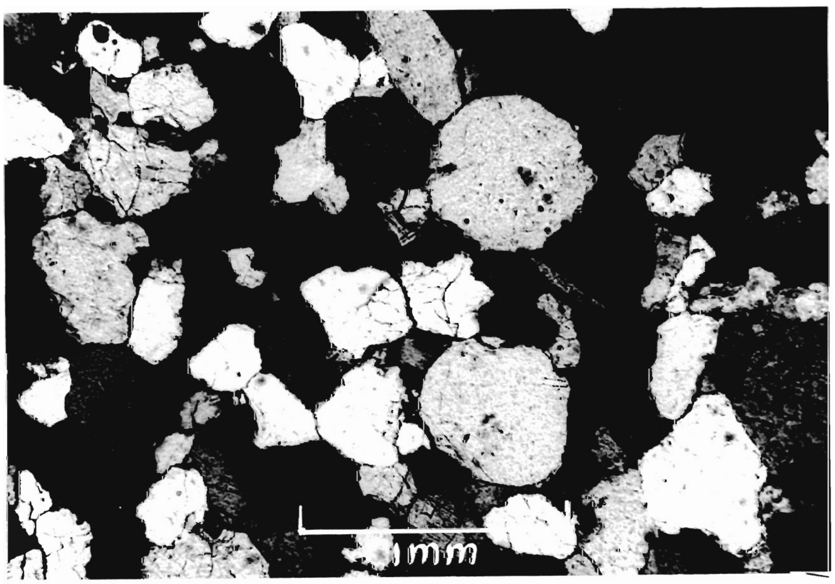


Fig. 114 - Photomicrograph of sandstone dyke. Crossed nicols. X 35.

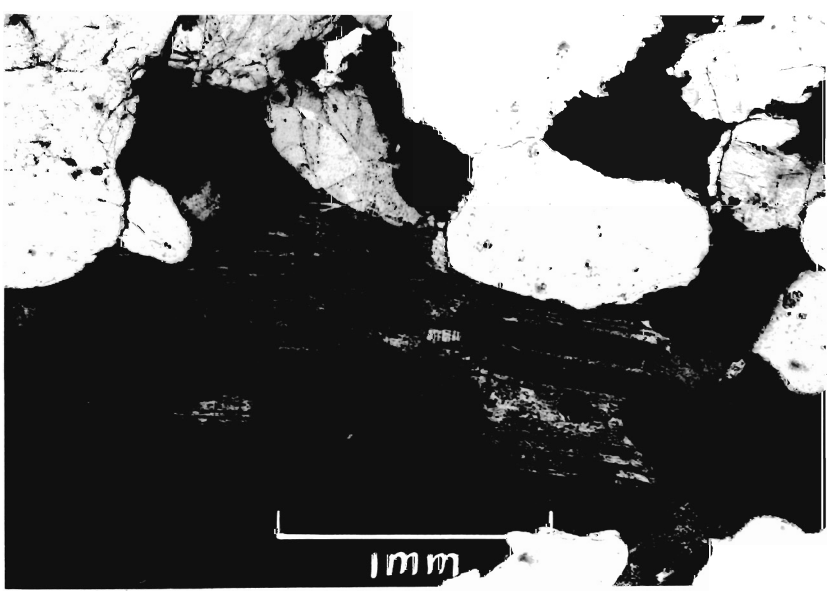


Fig. 115 - Photomicrograph of sandstone dyke (above) - porphyritic granite (below) contact. Note the solution and redeposition and the crushing and bending of plagioclase twin lamellae.
Crossed nicols. X 35

are Paleozoic of similar age so it is reasonable to assume that Paleozoic sands filled cracks at this time in the Mutton Bay area.

The assumption that the sandstone dykes are Early Paleozoic implies that (1) the rocks it cuts are older and, allowing for erosion of at least 1000 feet (sandstone dykes at sea level, highest point of syenite pluton 887 feet), puts the age of the syenite as Precambrian, and that (2) erosion since the Early Paleozoic has not cut deeply into the Late Precambrian land surface, and therefore the syenite stood as a resistant mass in Late Precambrian times as it does today.

GENERAL STRUCTURE

STRUCTURE OF THE LAYERED METAMORPHIC ROCKS

Exposure in the Mutton Bay area compares favourably with Western Greenland where an excellent structural study has been made by Berthelsen (1960) in gneisses similar to those of Mutton Bay. A detailed structural study is not the purpose of this thesis, and the only extra effort made in the field was the careful measurement of as many mineral lineations, minor fold axes, joints, shear planes, and foliations as possible in the course of normal geological mapping. Sufficient data was collected to work out the over-all structural picture and to obtain an idea of the structural history, the stratigraphy, and possible depth of burial of the rocks during metamorphism.

Berthelsen's (1960) study of the Touqussap Nunâ area was facilitated by the occurrence of several 'pyribolite' (pyroxene-bearing amphibolite with hornblende/pyroxene ratio of 1/2 - 2) marker horizons which are easily detectable. Such rocks in the Mutton Bay area do not have a wide occurrence and are also the most readily weathered. In the Mutton Bay area medium-grained pink granitic gneiss acts as suitable marker horizons that can be easily traced and are widespread. The lower marker, immediately above the coarse-grained porphyritic granite, is low in the stratigraphy and sufficiently often exposed at the surface by folding to be extremely useful. Other markers, useful only locally, include quartzites, mixed zones, and garnet-biotite-plagioclase gneisses. The coarse-grained porphyritic granite is itself a marker since it is generally conformable with the gneisses.

Much of the structure is well defined on the airphotos and this is confirmed and added to by lithological mapping. Structural readings provide the final clues for the determination of the over-all structural picture. For the structural analysis the area is divided into homogeneous domains. Identical adjoining domains have been combined so a minimum number of domains covering the major structures of the area are presented for discussion.

Foliation

Foliation is generally parallel to compositional layering and only west of Mutton Bay was axial plane foliation observed on a macroscopic scale. Accordian folds with cleavage in the axial zones have developed in a very micaceous gneiss (fig.116). In a more felspathic gneiss an axial plane foliation has developed which cuts the gneissosity, and is represented by quartz-felspathic veins filling a fracture cleavage (fig.117). Both the above axial plane foliations occur where there has been tight refolding of early recumbent folds. They probably developed at a late stage in the folding history, after the peak of metamorphism had passed and the rocks were becoming brittle. It is interesting that they strike E-W parallel to the nearby dyke-like mass of granite that probably intruded a fracture in the relatively brittle rocks. Most rocks of the area are very granular and crystallized under conditions that do not lend themselves to the development of axial plane foliations visible on a macroscopic scale.

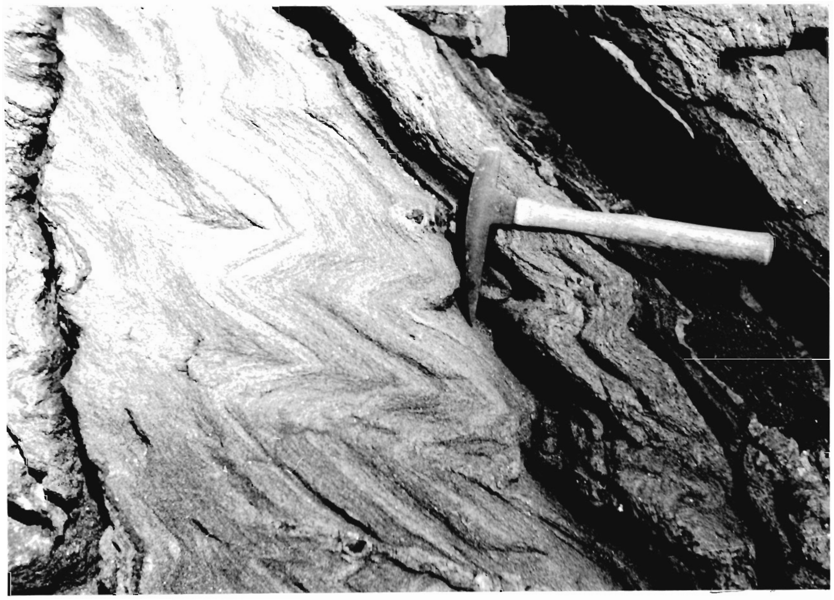


Fig. 116 - Accordian folds with an axial plane cleavage in a micaceous gneiss west of Mutton Bay.

Fig. 117 - Quartz-felspathic material filling an axial plane cleavage in a grey quartz-plagioclase-biotite-hornblende gneiss. West of Mutton Bay.

Lineations

Linear structures are displayed by most of the gneissic rocks, and include the corrugation of the foliation planes, axes of minor folds, pinch and swell structures, boudinage, and preferred orientation of minerals. Hornblende gives a strong lineation to the meta-gabbros. A lineation of quartz and felspar ellipsoids and of felspar phenocrysts is commonly present in quartz-felspathic gneisses and granite. Other minerals producing lineations are biotite, sillimanite, clusters of garnet, graphite, pyroxenes, and wollastonite. Except for some of the fold axes, most of the above lineations are b-lineations (parallel to major fold axes). Occasional lineations of micas in thin meta-gabbros are perpendicular to the b-lineations particularly near contacts, and are presumably due to slippage parallel to layering, and may be related to a late phase of folding.

Minor folds in the area are a reflection of the major folds. Those on the limbs of broad open folds are open folds (fig.118). Most folds measured have an amplitude to wavelength ratio of 1 : 10. Closed folds occur in the closures or noses of major closed folds (fig.119). Very complex minor folding about a single axis was observed in the anticlinal hinge east of Île aux Graines.

Minor folds whose axes are perpendicular to the main mineral lineation occur northeast of the Mutton Bay intrusion. They are generally open folds and include many pinch and swell structures. West of the Mutton Bay intrusion these folds are not conspicuous. Very open minor folds in domain 13 (fig.126, p.262) are neither parallel nor perpendicular to the major fold axis, and are believed

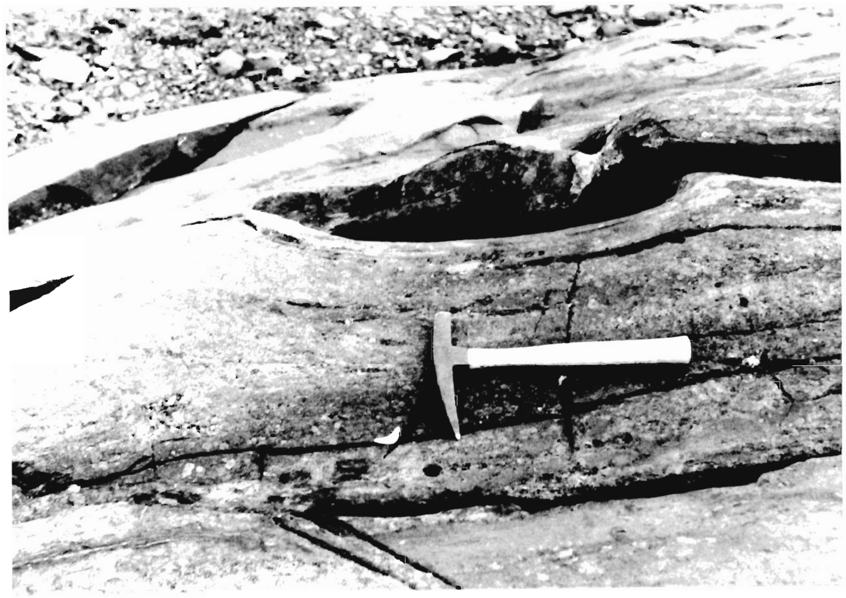


Fig. 118 - Open fold in meta-gabbro. Baie Querry.

Fig. 119 - Closed fold in green pyroxene-plagioclase gneiss. West of Mutton Bay.

related to minor open folding about a southeast axis which is parallel to the major fold in domain 14 (fig.126, p.262). This indicates that the folding continued after crystallization of the linear minerals.

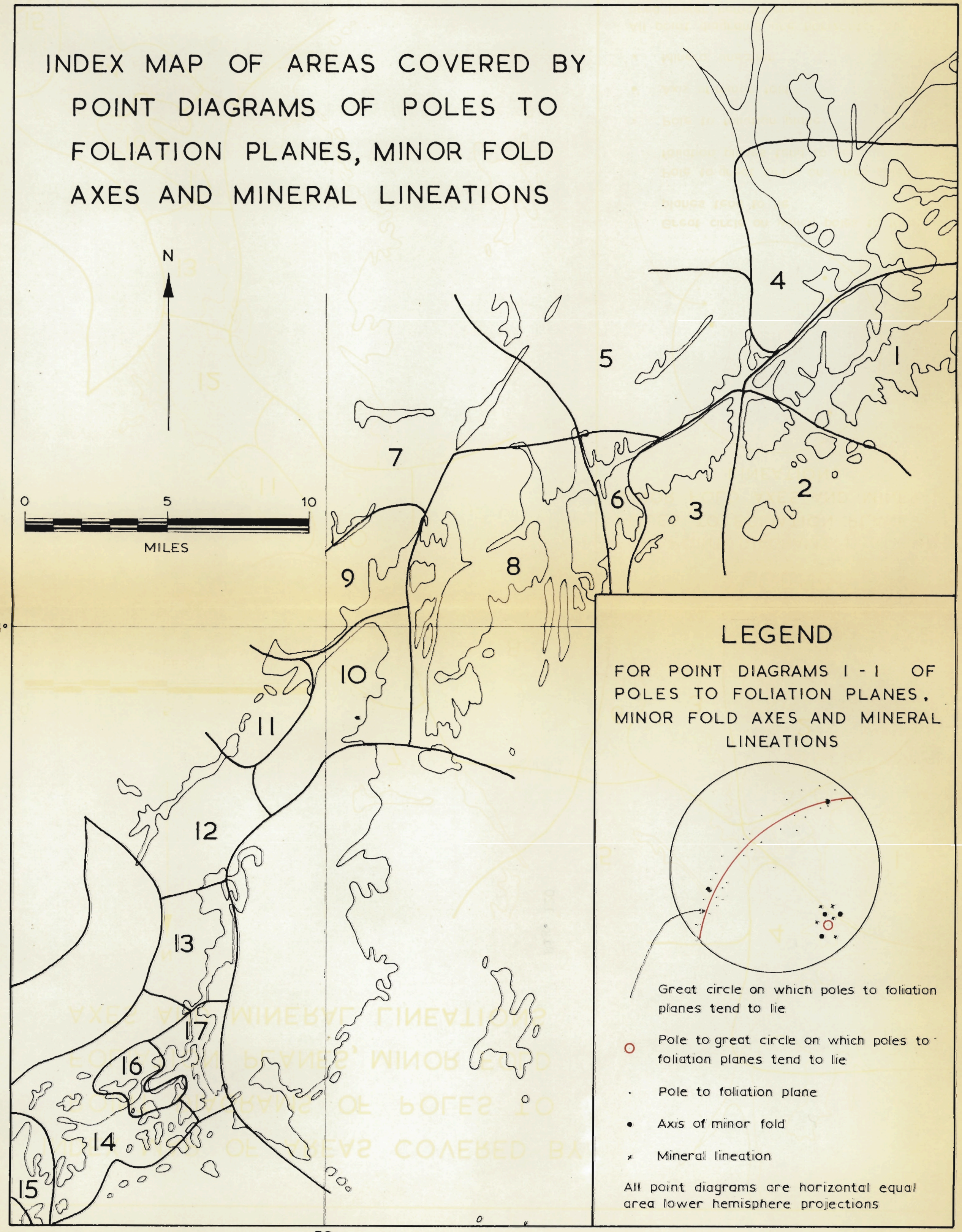
Description and Analysis of Structural Domains in the layered metamorphic rocks

For the purpose of structural analysis the area is divided into 17 domains (fig.120), and for each domain a point diagram of poles to foliation planes, minor fold axes, and mineral lineations is presented (figs.122-3 and 125-7). The northern part of the St. Augustin map sheet is discussed separately as a single unit because there are insufficient structural readings to warrant subdivision.

St. Augustin Area

The structure of the rocks of the St.Augustin area is at first sight relatively simple. The nose of a small north-plunging synform overturned to the west is evident at Rivière Thunay (fig.121) and a basin inclined to the southwest is centred on St. Augustin Bay. Strikes are generally NNW and dips are to the ENE. Between Rivière St-Augustin - Nord-Ouest and Lac Fréjean is a sequence of alternating layers of green pyroxene-plagioclase gneiss and pink granitic gneiss. To the southwest of the above sequence is the St.Augustin porphyritic granite dome, and to the northeast is a thick grey biotite gneiss recognized nowhere else in the area.

There is evidence that the above structures are not the only ones present. At the eastern boundary of the area on the south side of Passage Bougainville occurs what appears to be the nose of a



INDEX MAP OF AREAS COVERED BY POINT DIAGRAMS OF POLES TO FOLIATION PLANES, MINOR FOLD AXES AND MINERAL LINEATIONS
N
0
5
10
MILES
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
51°
59°
LEGEND
FOR POINT DIAGRAMS 1 - 1 OF POLES TO FOLIATION PLANES, MINOR FOLD AXES AND MINERAL LINEATIONS
Great circle on which poles to foliation planes tend to lie
Pole to great circle on which poles to foliation planes tend to lie
Pole to foliation plane
Axis of minor fold
Mineral lineation
All point diagrams are horizontal equal area lower hemisphere projections

Fig. 120

Fig. 121 - Reproduction of aerial photograph (R.C.A.F.) showing the north-plunging Rivière Thunay synform which is overturned to the west, and the right-hand displacement on the Rivière Thunay valley fault.
Scale : 2 inches = 1 mile

southeast-plunging antiform overturned to the southwest. Along strike two miles northwest of Riusseau Donais is another possible closure. Two mineral lineation measurements west of this closure plunge southeast and one to the east plunges northwest, but further along strike, north of Étang Belon, mineral lineations plunge north as in the Rivière Thunay synform. Exposure west of Étang Belon is poor and there is a lack of structural measurements, but the trend of layering and airphotos suggest that a closure occurs here also. Evidence points to the structure being a doubly-plunging antiform. East of the indicated antiform the dip of the layering decreases as expected. The grey biotite gneiss of Lac Fréjean is apparently a part of a synform, overturned to the west, which supports the hypothesis of there being an antiform to the southwest.

The lithology is not well defined and a correlation of layers along strike must take into account large left-hand displacements on the Ruisseau Donais and Passage Bougainville linears evident on airphotos. However, reasonable correlations can be made which fit the structural interpretation. The pink granitic gneiss, well developed in the anticlinal region, may be equivalent to the thick pink granitic gneiss of the St. Augustin basin and Étang Tardivet. The grey biotite gneiss west of the Rivière Thunay synform may be equivalent to the biotite gneiss in the zone along the contact with the Lac Fréjean biotite gneiss synform.

The over-all picture for the St. Augustin area north of the St. Augustin basin is shown in cross-section I-J-K (in back pocket). Gneisses are folded about a NNW axis with overturning to the WSW, and this was followed or accompanied by a NNE phase of open folding. Most mineral lineations parallel the NNW fold axes but rare lineations in amphibolites plunge perpendicular to them. It must be appreciated that this is the least accessible and the poorest exposed part of the map area. Insufficient readings of mineral lineations and minor folds were made for a proper structural analysis. The St.Augustin basin is much better exposed and structural data from it is included in the stereogram of domain 4.

Domain 1 (fig.122)

Domain 1 is composed of gneisses strongly injected by porphyritic granite. It is considered part of the St. Augustin basin and is connected to the synform of domain 2 by a southeast-plunging antiformal hinge lying immediately northeast of Île aux Graines and Les Îles Mack.

Foliations on Île de la Grande-Passe and Île de la Conserverie suggest the presence of an overturned northwest-plunging synform which in turn implies the presence of an overturned antiform to the east connecting it to the St.Augustin basin. However, the synform is no longer apparent when the left-hand displacement on the Grande Rigolet fault is considered, and the gneisses simply wrap around the mass of porphyritic granite on Île du Petit-Rigolet.

Domain 2 (fig.122)

The structure of domain 2 is an extremely well defined open synform plunging to the southeast and strongly injected by porphyritic granite. The axial plane of the synform has been displaced about 3/4 mile sinistrally by the Grande Rigolet fault.

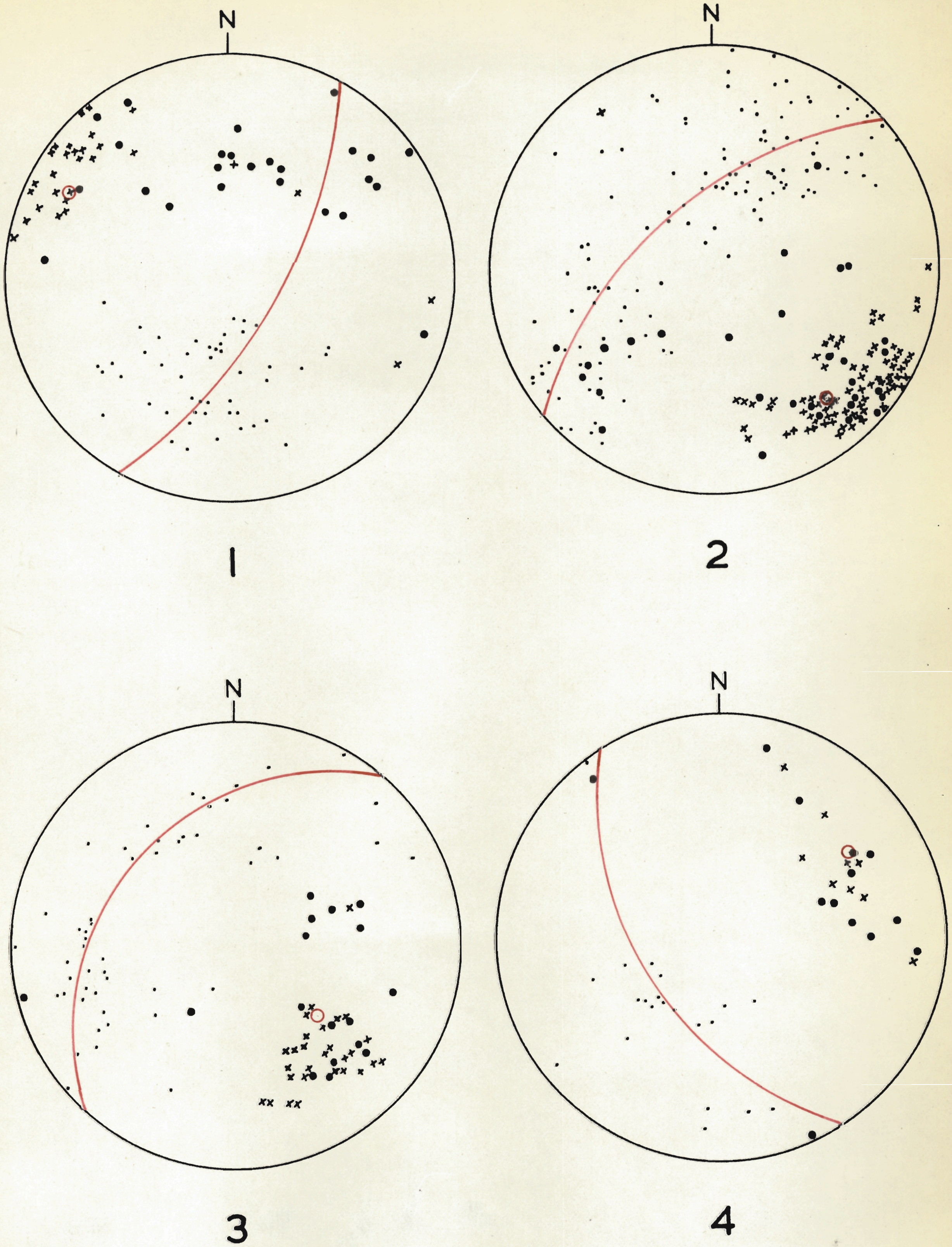


Fig. 122 - Point diagrams of poles to foliation planes, minor fold axes and mineral lineations. For legend see fig.120, p.250.

Domain 3 (fig.122, p.254)

Domain 3 includes an open synform, plunging southeast, adjoining a closed antiform overturned to the southwest in the southwest part of Havre de l'Aigle. The synform of domains 2 and 3 are no doubt connected by an antiform.

Domain 4 (fig.122, p.254)

Domain 4, including Baie des Oies, is small and lineations are believed related to the St.Augustin basin.

Domain 5 (fig.123)

Domain 5 is strongly intruded by porphyritic granite and consists essentially of a north-plunging antiform overturned to the west. On the upper limb of the antiform is a very open synform.

Domain 6 (fig.123)

Domain 6 consists essentially of the central part of the west limb of the overturned antiform of domains 3 and 5. Mineral lineations are nearly horizontal and strike N-S. Domain 6 forms the link between the southeast-plunging lineations of domains 2 and 3 and the north-plunging lineations of domain 5. Treating domains 2, 3, 5, and 6 as a unit, the structure may be described as an overturned antiform on whose upper limb were formed subsidiary synforms. The axis trended NNW but was folded about a ENE to NE axis by a later phase of folding. It is probable that the second fold was causedby the diapiric intrusion of porphyritic granite. The intrusion of granite accounts for the spread of lineations and foliations.

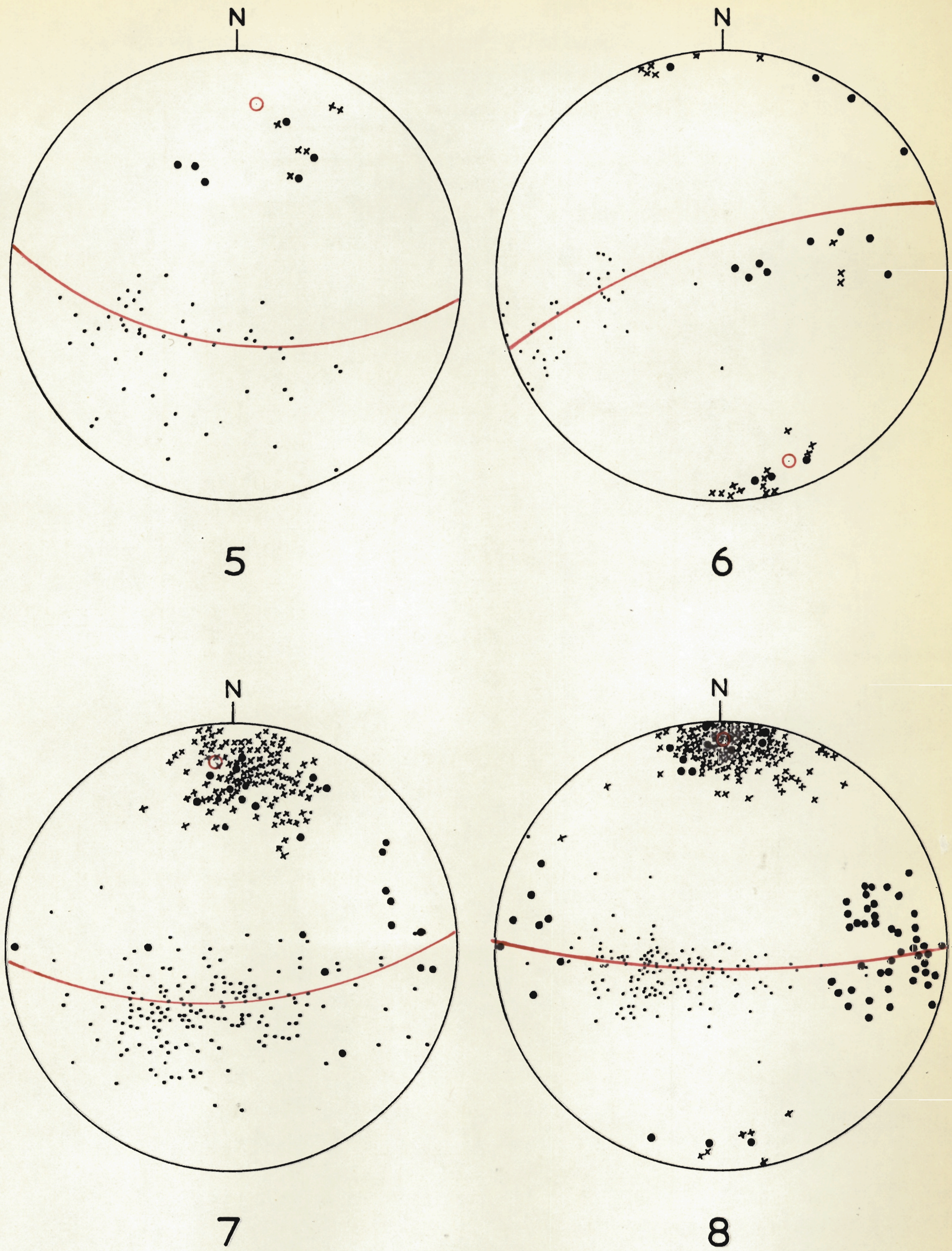


Fig. 123 - Point diagrams of poles to foliation planes, minor fold axes, and mineral lineations. For legend see fig.120, p.250.

Domain 7 (fig.123, p.256)

Domain 7 has a consistant fold axis plunging north, and consists of a series of folds most of which are overturned to the west. However, at the west end of Lac Trois-Millesis an open synform, with an antiform and a synform to the east of it, overturned to the east. This is followed eastward by an open antiform, a synform overturned to the west, and then a very tight antiform (fig.124) overturned to the west. Between the tight antiform and the granite of Lac Théberge is a suspected synform overturned to the west. Two easily weathered, closely spaced horizons occur on both limbs of the antiform and are repeated again to the northeast (fig.124). Other evidence for the synform is the slight increase in dip on the supposed northeast limb of the synform, and the two pink granite gneiss layers which can reasonably be correlated.

Domain 8 (fig.123, p.256)

Domain 8 is structurally much the same as domain 7. Plunges of lineations and fold axes are mostly to the north, with some south or horizontal. The suspected synform and tight antiform northwest of Lac Kécarpoui apparently continue south into this domain. North of Baie Querry is an open antiform and synform. The conspicuous occurrence of garnetiferous grey biotite gneiss in pink granitic gneiss at several points in the domain suggests a correlation of these pink granitic gneiss layers. This correlation indicates the presence east of the two open folds of a tight synform overturned to the west. To the west of the open folds is an antiform with a north-plunging nose at the north end of Baie des Ha! Ha! and another west of Baie Querry. The antiform is

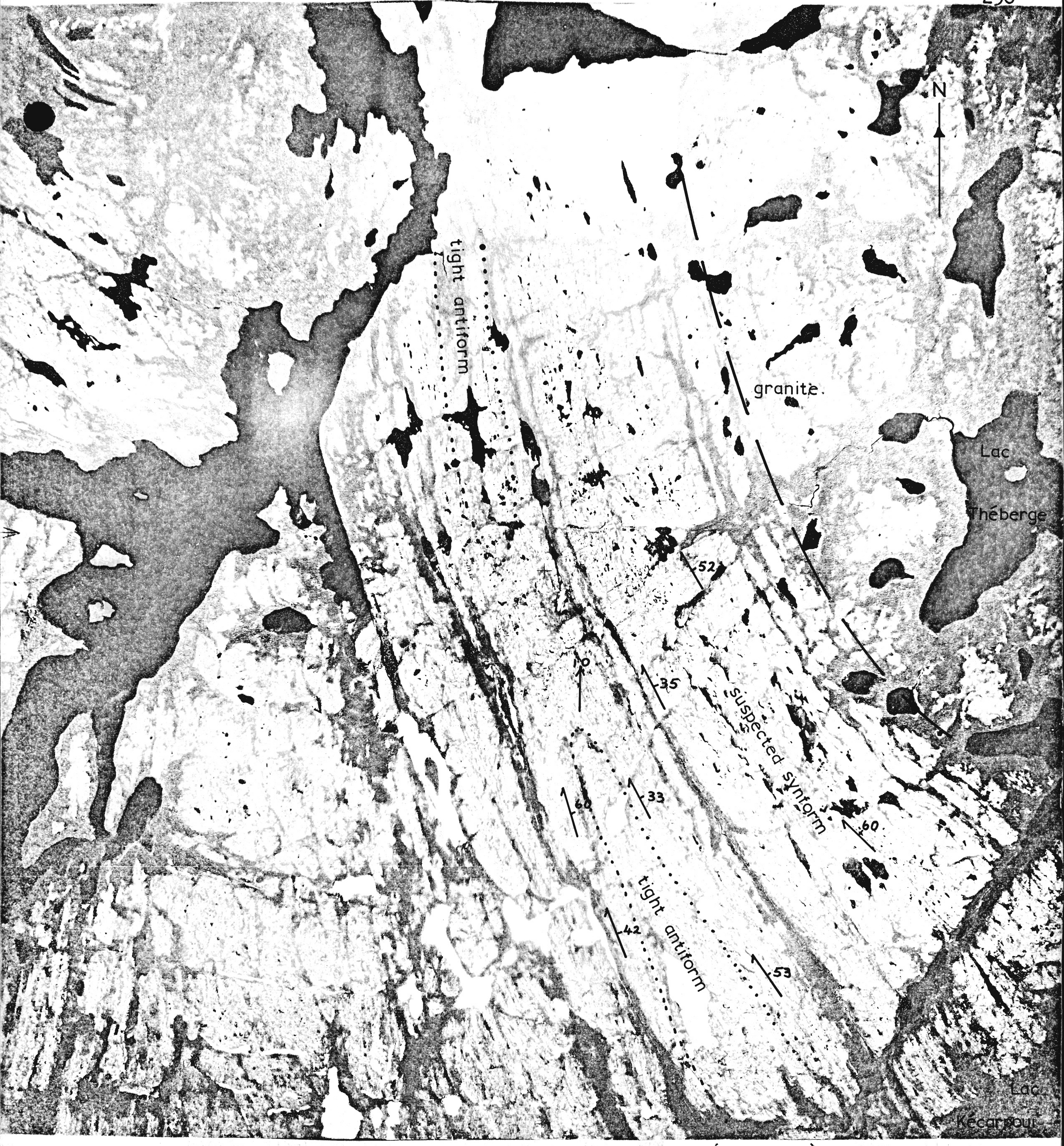


Fig. 124 - Reproduction of aerial photograph (R.C.A.F.) northwest of Lac Kécarpoui showing a tight antiform overturned to the west and the Lac Théberge granite between which is a suspected synform. Two easily weathered layers (dark) occur on both limbs of the tight antiform and are repeated again to the northeast near the Lac Théberge granite.
Scale : 2 inches = 1 mile

generally overturned to the west. West of this antiform is a synform clearly exposed east of Baie des Ha! Ha! where it is overturned to the west and plunges north. Further north the structure is less obvious but the quartzites of Baie des Ha! Ha! can be traced to Lac du Chevreuil.

Domain 9 (fig.125)

Domain 9 is one of transition between domains 7 and 8 and domains 10, 11, and 12.

Domain 10 (fig.125)

Domain 10 is a doubly plunging antiform with a core of pink granite gneiss believed to be the layer lying just above the coarse-grained pink porphyritic granite. Lineations are in part oblique to the major NE fold axis, suggesting that the NE fold axis represents a young phase of folding superimposed on an old N-S lineation.

Domain 11 (fig.125)

Domain 11 is a doubly plunging synform which shows s strong scatter of lineations as in domain 10. Axis of the major fold strikes NNE but many of the lineations strike to the ENE, suggesting in this case that an old ENE lineation has a younger NNE phase of folding superimposed upon it. It is obvious that the suggested old lineations in domains 10 and 11 are not compatible and the best explanation for the spread of lineations in both domains is that they are a result of the non-cylindrical nature of the folds.

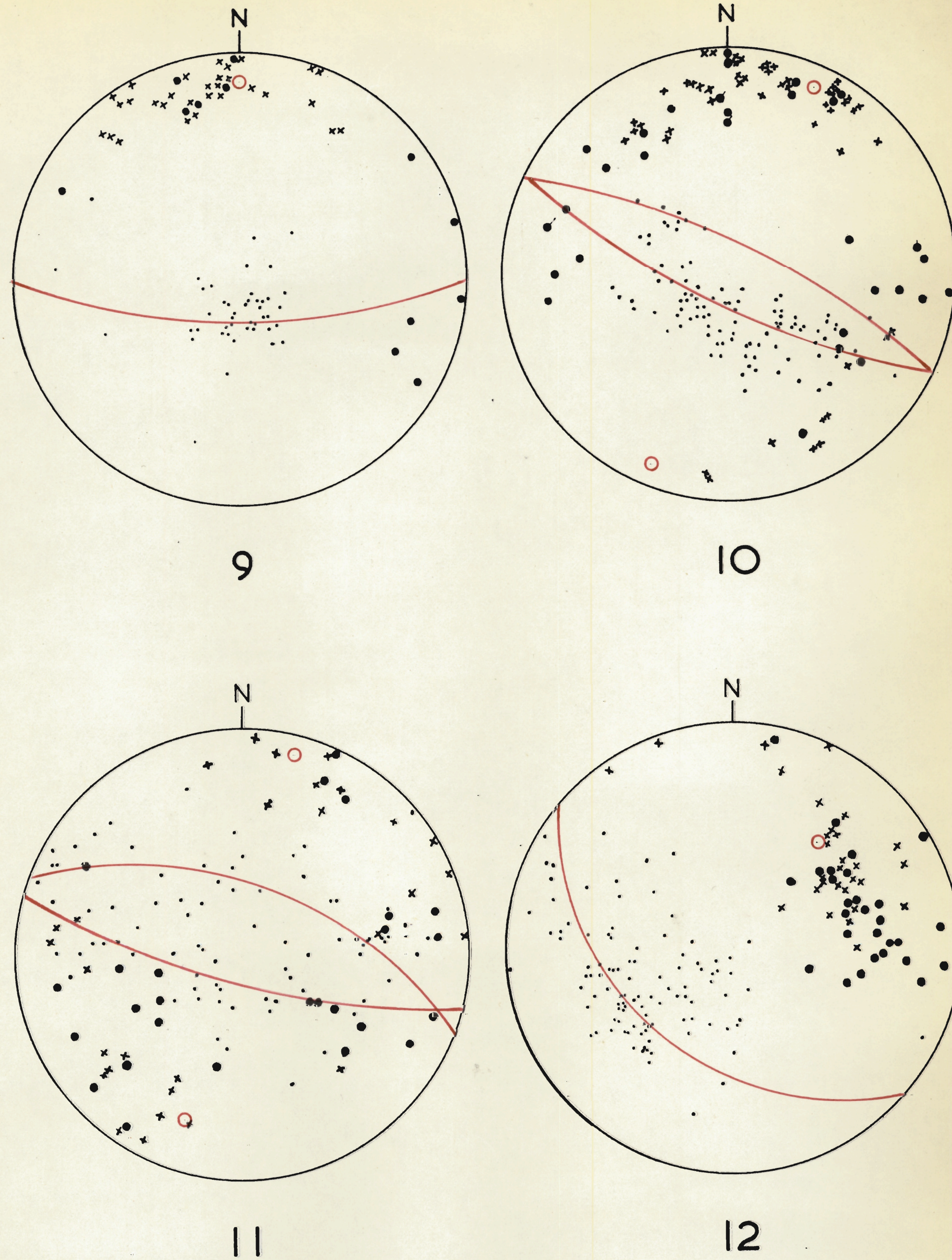


Fig. 125 - Point diagrams of poles to foliation planes, minor fold axes, and mineral lineations. For legend see fig.120, p.250.

Domain 12 (fig.125, p.260)

Domain 12 is another well-defined synform plunging ENE to NE and overturned to the NW. It is separated from domains 10 and 11 by a similarly overturned antiform. The open synform and antiform of domains 10 and 11 lie on the upper limb of the overturned antiform and are folded about the secondary NE fold axis common to the whole area. The folds of domains 10 and 11 also occur in a transition zone where the ENE trend of domain 12 changes to the N-S trend of domains 7 and 8.

Domain 13 (fig.126)

Domain 13 contains a synform which is the south-plunging counterpart of the ENE-plunging synform of domain 12. The synform is folded about a N-S to SE axis and is overturned to the west. Of interest is the discordance between mineral lineations and minor fold axes, suggesting that the minor folds were later than the lineation.

Domain 14 (fig.126)

Domain 14 consists of another part of the synform found in domain 13. Lineations here parallel the minor folds. At the coast the overturned synform has been folded about a NE to ENE synformal axis and is overturned to the NW.

Domain 15 (fig.126)

Domain 15 is also part of the synform of domains 13 and 14. The plunge of its lineations is intermediate between those of domains 13 and 14 and could have been affected by the adjacent porphyritic granite.

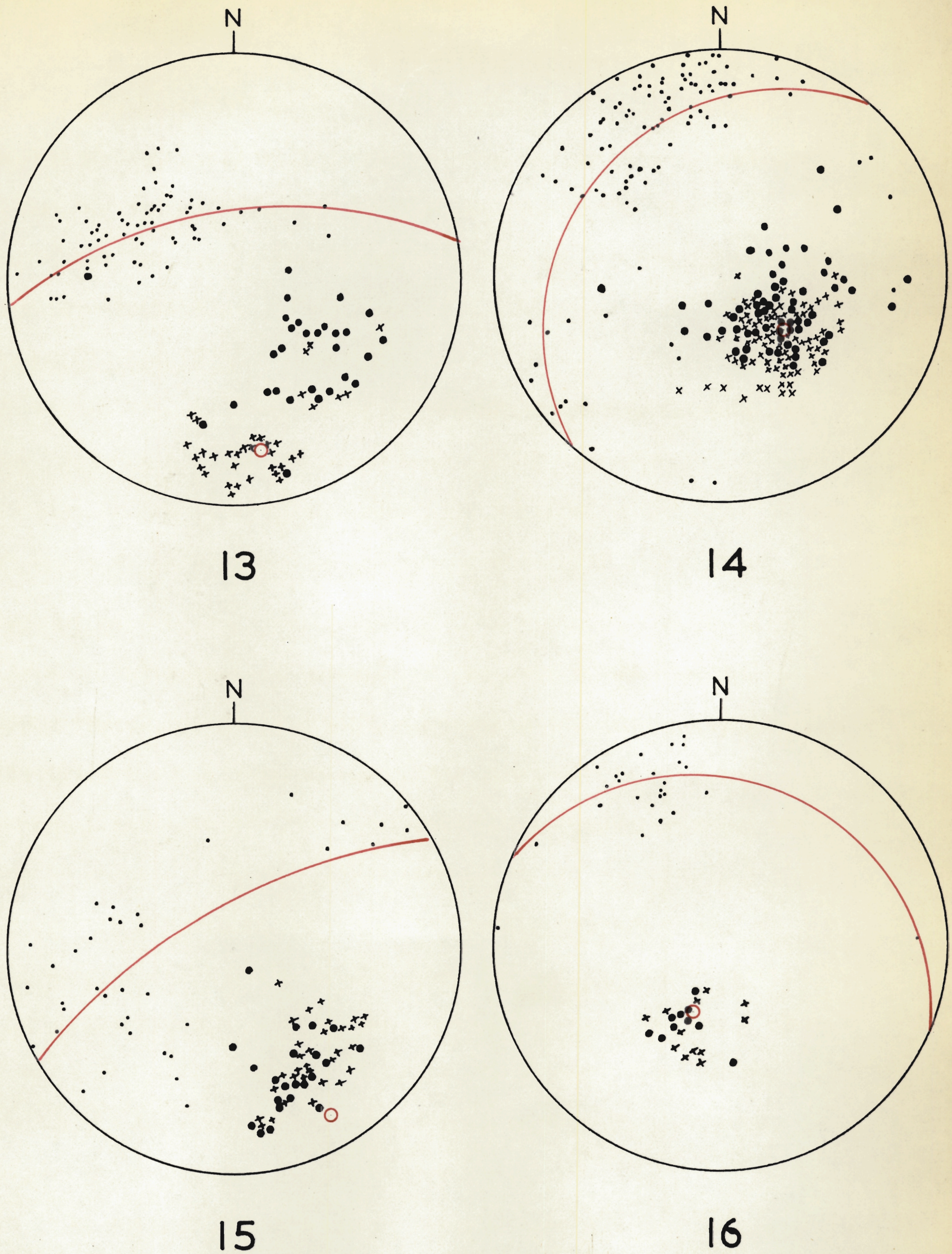


Fig. 126 - Point diagrams of poles to foliation planes, minor fold axes, and mineral lineations. For legend see fig.120, p.250.

Domain 16 (fig.126, p.262)

Structures of domain 16 are similar to those of domains 13-15. Included in domain 16 is the overturned synform superimposed on the major overturned synform of domains 13 and 14. The superimposed NE fold has folded the earlier lineations but structures believed related to the refolding are found in domain 17.

Domain 17 (fig.127)

Domain 17 is related to domains 13-16. It also contains a lineation measurement which may belong to the refolding. Within this domain were seen refolded minor folds which are believed to display the pattern of the major structure.

Discussion

The over-all picture of the area shows that the porphyritic granite has greatly influenced the fold pattern. Areas injected and closely underlain by the granite have fold axes and mineral lineations striking northeast or northwest, whereas those free of granite have very consistent north and SSE plunging axes and mineral lineations. Folding apparently started about, or followed, an early north to NNW axis, indicating an E-W compression which coincides with the maximum compression deduced from a study of the early joint systems. This is the general trend of the Grenville A Subprovince and is close to that of the Labrador Trough, which suggests a possible relation.

The porphyritic granite is synkinematic and intruded in a diapiric fashion accompanied by overturning to the west. Gneisses ahead (west) of the intruding granite were intensely folded. It

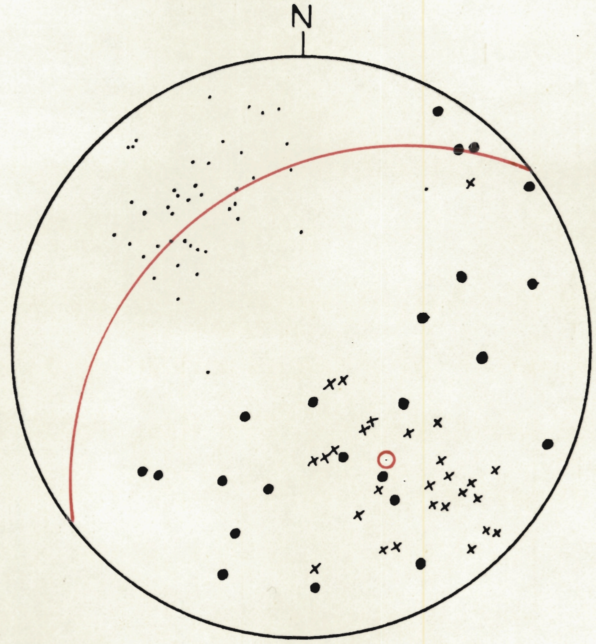


Fig. 127 - Point diagram of poles to foliation planes, minor fold axes, and mineral lineations. For legend see fig.120, p.250

is interesting that the only fold overturned to the east is far removed from the granite. Domains closely associated with the porphyritic granite have fold axes that strike northeast or northwest and are parallel to axes of elongation of the granite masses. The shape and symmetry of a diapiric granite mass intruding a folded sequence will be influenced by the axis of the intruded folds and this will be reflected in the symmetry of the diapir's satellitic folds. The axes of folds associated with the porphyritic granite in the area appear to have been resolved into two directions oblique to the original N-S direction.

The diapiric intrusion was accompanied by metamorphism and mineral lineations developed parallel to both early and late fold axes, whichever axis was the direction of maximum transport. The effect of the late folding on the early folding where the latter is furthest removed from the influence of the granite is to warp the early folding about a northeast axis.

The overturned synform of Lac du Gros-Mécatina, which is refolded into a second overturned synform, demonstrates that even tight refolding need not produce a new mineral lineation. This fold and the cross-fold separating the Lac du Gros-Mécatina synform from the Lac à Charles synform represent a cross-fold that results from the formation of the second phase of diagonal folds associated with the diapiric granite. They did not involve a great amount of transport of material parallel to their axes and they may be considered a third phase of folding which is a necessary result of the second phase.

Minor open folds, which developed northeast of Mutton Bay perpendicular to the major fold axes, are believed to be cross-folds related to the major folds. Hungerer (1922) was the first to experiment with cross-folding and showed that an inhomogeneous elastic prism, such as rubber, arches into a saddle-shaped anticline when compressed unilaterally. Plasticine behaves similarly as shown in fig.128. Argand (1912) first proposed that, in the Alpine nappes, main and cross-folds are simultaneous. Since then many authors have suggested that in many metamorphic rocks the main and cross-folding are synchronous. Bhattacharji (1958) studied cross-folding from a theoretical and experimental point of view. His work suggests a contemporaneous origin of right-angle cross-folds and he showed mathematically that flow is in part parallel to the fold axis. There is buckling of the axis of the fold as shown in fig.128 and this explains much of the minor cross-folding of the area. It explains why the minor cross-folding is at right angles to the major folding. There was one phase of folding with two components as in the development of boudinage.

All the folding in the area may be considered contemporaneous, but can be divided into phases based on the order in which the individual folds make their appearance. The earliest folds were N-S and possibly represent an early phase revived at a later date. Diapiric granite intrusion gave rise to a second phase of diagonal northeast and northwest folds which were followed by a third E-W phase. Each major phase had its own related cross-folds.

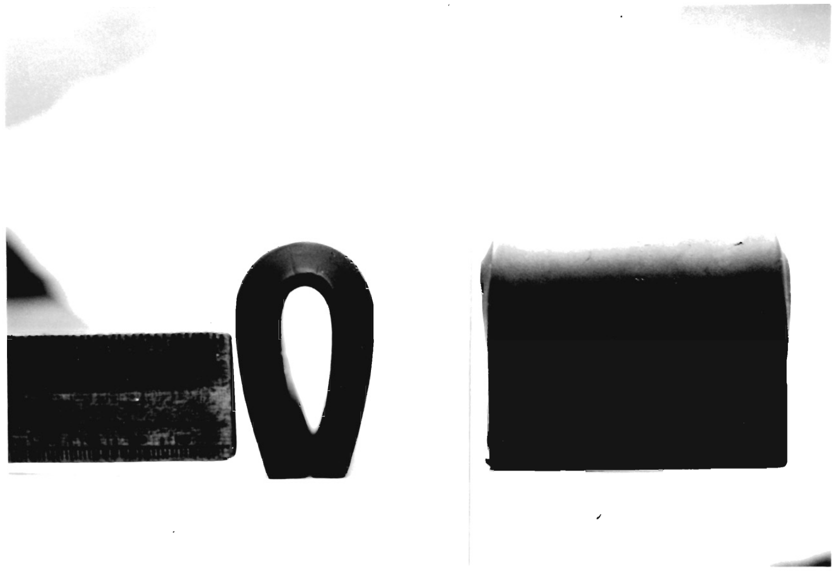


Fig. 128 - Cross-fold (right) on the crest of a closed fold (left), produced in slab of modeling clay. Scale marked in inches (above) and centimeters (below).

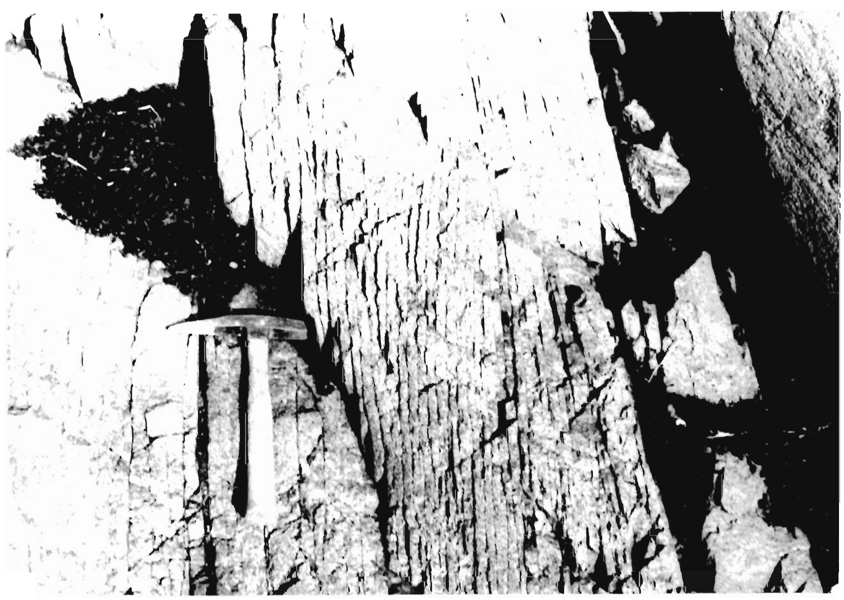


Fig. 129 - A zone, 4 feet wide, of close-spaced jointing with red alteration in green pyroxene-plagioclase gneiss.

Faults

Early minor faults

Early minor faults with small displacements are numerous (fig.22, p.60). Most are not particularly susceptible to weathering. Their fractures have healed and dragging of the country rock against the fault plane is a common feature. They formed at about the same time as the intrusion of the intermediate dykes under conditions where the rocks could fracture, but also behave plastically, and metamorphism was still active.

Late faults

Late faults, whether minor or major ones, are deeply weathered and very few are actually seen. They are accompanied by a zone of closely spaced jointing or fracturing (fig.129, p.267, and fig.130) with red alteration of the fractured rock. Fracture zones occur along all the linear valleys and are conspicuous along submerged valleys in the coastal part of the area. They commonly contain quartz, epidote, and carbonate veins. At the bottom of Baie des Ha! Ha! a fracture zone, probably related to the Petit Rigolet fault, is cut by two younger dykes, indicating a pre-Ordovician age for the start of the faulting.

Major faults in the area have resulted in the formation of linear valleys (fig.131). Not all the valleys can be proved to be fault-line valleys, but many are, and it is reasonable to assume that many of the others are too.

The most spectacular fault is that running from Lac à Charles across Baie des Ha! Ha!, and along Petit Rigolet to Gros Île. It is difficult to correlate beds across the fault but the general pattern

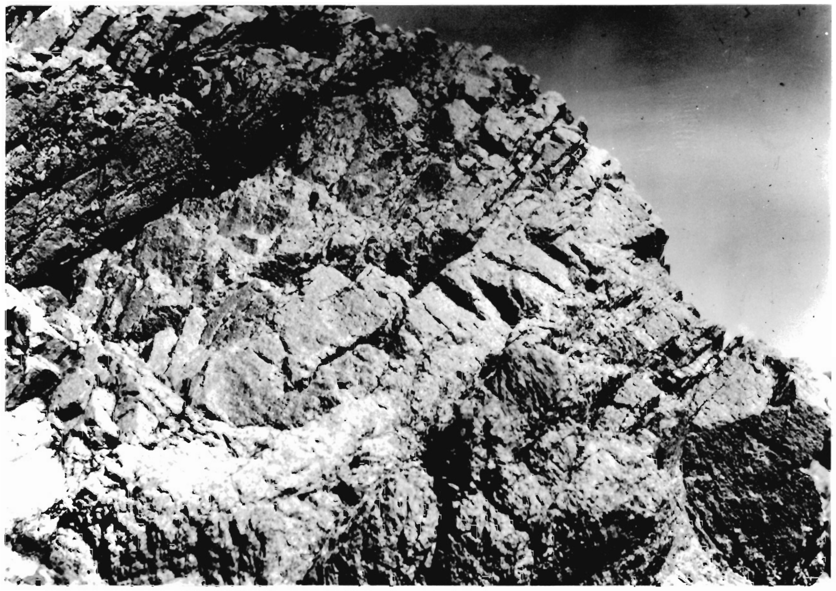


Fig. 130 - A wide zone of strongly fractured gneiss with red alteration related to the Petit Rigolet fault.

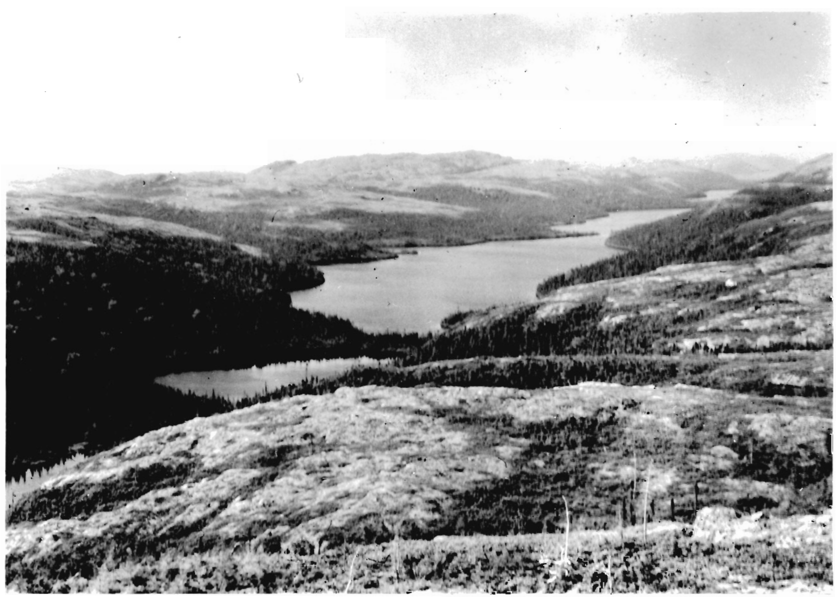


Fig. 131 - The linear valley occupied by Ruisseau Donais. View from the headwaters of the river towards the southwest.

is consistent with a left-hand displacement of about 1/4 mile. Of considerable interest is the left-hand displacement of the two giant Ordovician dykes by this fault. The smaller dyke, 1 mile east of Anse de l'Argile, is offset about 1/8 mile on crossing Petit Rigolet, which may be due to post-dyke faulting or to the dyke having intruded a fracture zone that had already been faulted. The larger dyke is not exposed south of Petit Rigolet, but is represented by Passage Fournier, and a comparison of the strike of Passage Fournier with that of Anse Tucker indicates a lateral displacement similar to that of the smaller dyke. The similar displacements of the two dykes favours faulting as the cause. There is no tapering of the dyke at the fault as would be expected if the dyke had intruded a fracture that ended at the fault. Petit Rigolet is the result of erosion of rock that was sheared and faulted. An unsheared igneous rock that acts as a positive topographic feature elsewhere would be expected to form a resistant headland, but it does not and was therefore probably sheared itself. All the evidence points to the smaller dyke being faulted and its displacement provides a measure of the total lateral movement along the fault since Ordovician time.

A study of the Île aux Graines - Les Îles Mack fold shows that the Grande Rigolet fault has a left-handed horizontal displacement of 3/4 mile and a negligible vertical displacement. The Lac Kécarpoui fault has a left-hand horizontal displacement of about 1/4 mile. The fault between Baie de Kécarpoui and Baie Lessard is also left-handed, with about 1/10 mile horizontal displacement. On the St.Augustin sheet, the Rivière Thunay fault is apparently right-handed, and belongs to the NNE set of linears generally occupied by dykes. Displacement on the above faults is supported by lithological mapping.

The Passage Bougainville fault has displaced both N-S and E-W linears, the latter apparently a fault itself (fig.132). The Ruisseau Donais fault appears to displace a number of minor linears (fig.133) as well as the E-W linear mentioned above. Both Passage Bougainville and Ruisseau Donais faults have left-hand displacements, while the E-W linear has a right-hand displacement.

Kumarapeli and Saull (1966) have put forward arguments stressing the rift valley nature of the St.Lawrence valley. The branching of the rift around Newfoundland is a common feature of rift systems and has been produced experimentally. This being the case it would be unlikely to find right-handed movements on faults in the Mutton Bay area unless there was a thrusting of Newfoundland towards the continent. The movement of Newfoundland is, as suggested by Kumarapeli and Saull (1966), towards the sea.

Regional joints and their relation to dykes, topographic linears, and faults

A study of the joint history of the area includes the intimately related topographic linears, faults, and dykes. Joint systems can be both regional or local with superposition common. They may also be of different ages.

Dykes, topographic linears, and faults

The various dyke systems in the area offer a clue to the joint history. The intermediate dykes intruded after regional folding but during the end phase of regional metamorphism. They occupy joints that are the first to have formed

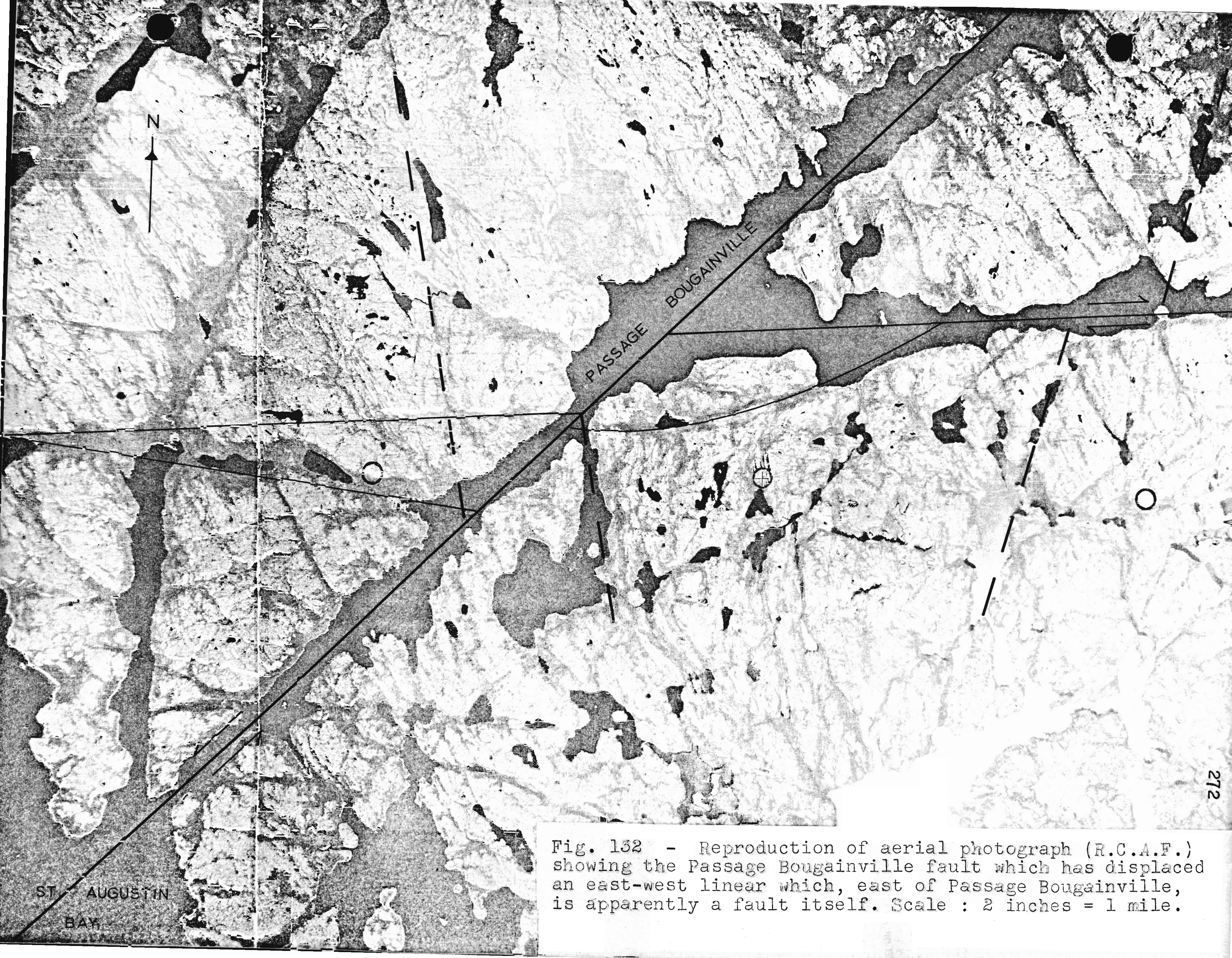


Fig. 132 - Reproduction of aerial photograph (R.C.A.F.) showing the Passage Bougainville fault which has displaced an east-west linear which, east of Passage Bougainville, is apparently a fault itself. Scale : 2 inches = 1 mile.

Fig. 133 - Reproduction of aerial photograph (R.C.A.F.) showing the displacement of linear features across the Ruisseau Donais valley fault. Movement appears to be left-handed. Scale : 2 inches = 1 mile

after the peak of metamorphism and the orientation of the dykes (early joints) is shown in fig.134. Presumably pre-existing joints, including local ones related to folding, were healed during metamorphism. A clue to the pre-metamorphic jointing might be obtained from a study of folded dykes, but these are rare in the area.

Satellitic dykes of the syenite pluton indicate the joint orientation in the syenite immediately after its consolidation (fig.135). The orientation pattern is the same as that of the intermediate dykes. However, in the latter the dominant direction is east-west, suggesting that these dykes occupy tension joints and the other joints, at 45^{o} to the east-west set, are shear joints caused by an east-west compression or north-south tension. In the syenite the compression or tension was from all sides and if, as it appears, the satellitic dyke pattern is the regional pattern, each joint direction opened to the same degree. It may be concluded that the joint pattern up to the time of the Mutton Bay intrusion was as in fig.134.

Topographic linears are parallel to faults and dykes and this fracture system probably came into being after the intrusion of the Mutton Bay syenite. Satellitic dykes of the syenite do not follow this pattern but an earlier one. The above fracture system existed before the intrusion of the giant Ordovician dykes and the relation between the faults and dykes indicates the stress conditions present during the Ordovician period.

Fig.136 is a sketch map showing the orientation of linear valleys in the region. A Rose diagram of regional topographic linears, fig.137, is compared with a Rose diagram of the observed

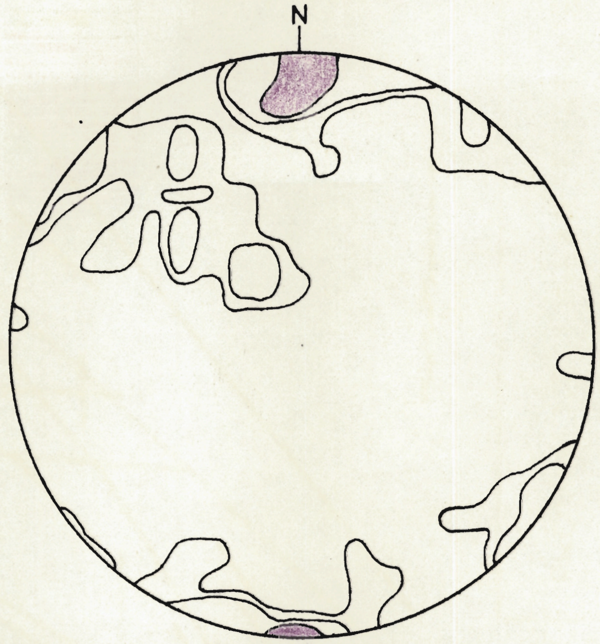


Fig. 134 - Contoured upper hemisphere equal area projection of poles to 89 intermediate dykes in the area. Contours 2, 3, and 5 percent per 1 percent area.

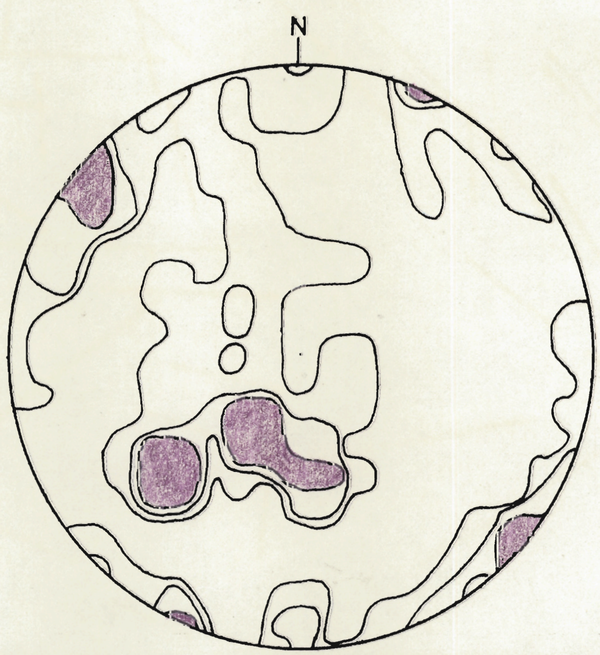


Fig. 135 - Contoured upper hemisphere equal area projection of poles to 92 aplite dykes in the Mutton Bay intrusion. Contours 1, 3, and 5 percent per 1 percent area.

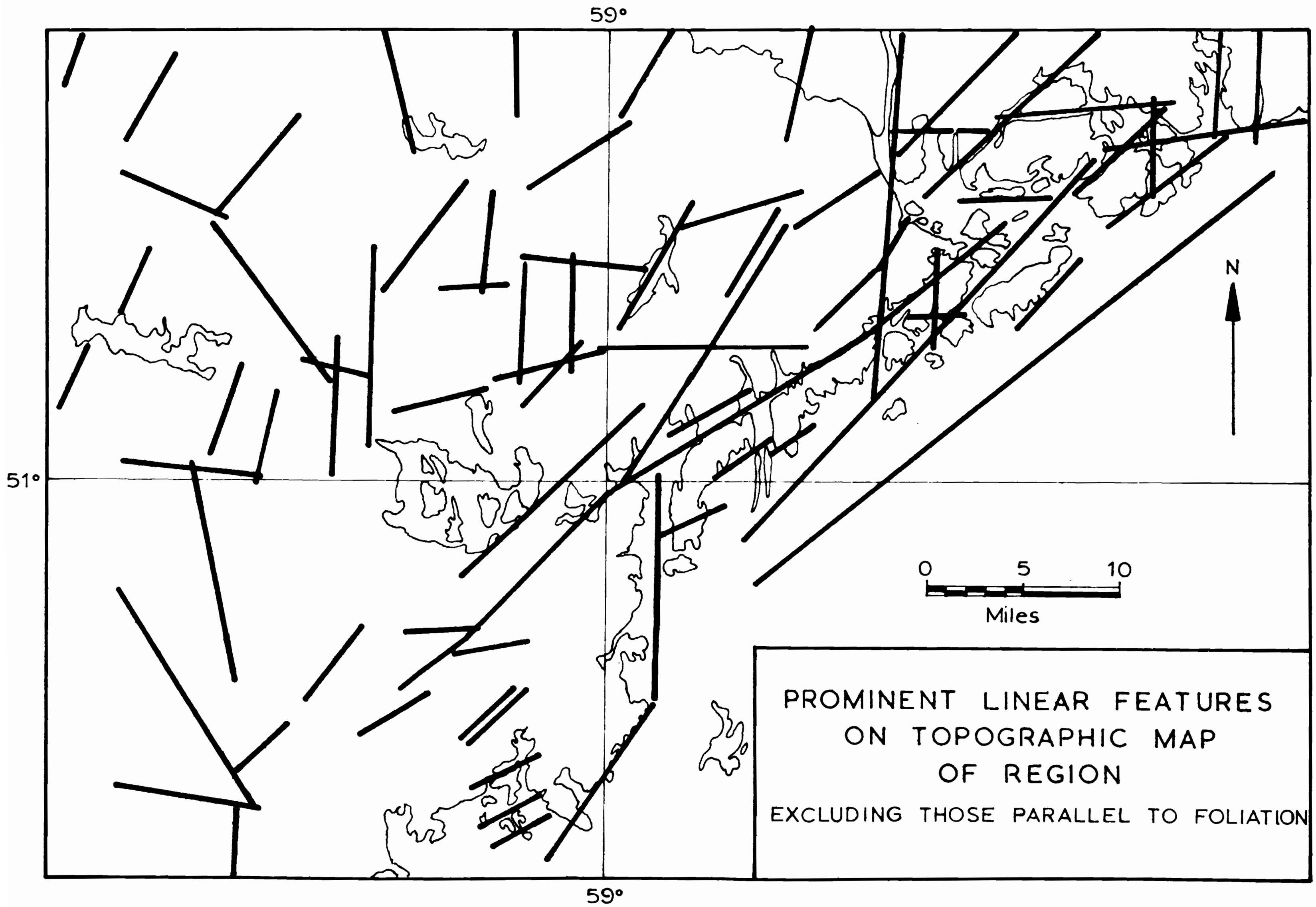

59°
59°
51°
51°
N
0
5
10
Miles
PROMINENT LINEAR FEATURES
ON TOPOGRAPHIC MAP
OF REGION
EXCLUDING THOSE PARALLEL TO FOLIATION

Fig. 136

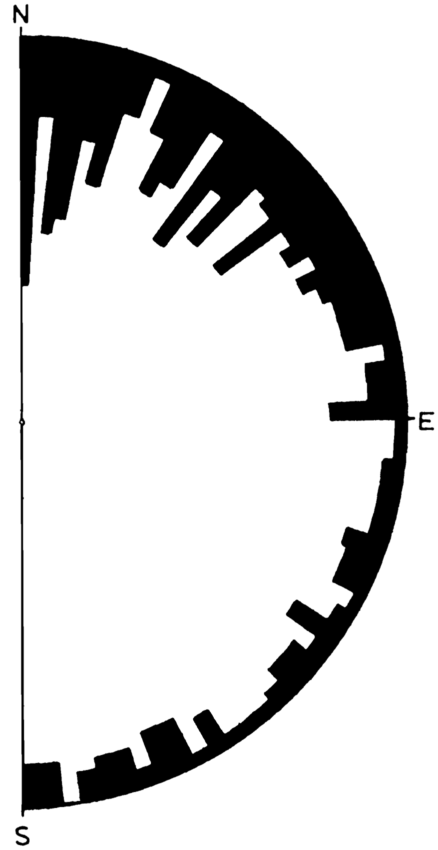


Fig. 137 - Rose diagram of regional topographic linears between 60°00'W and 58°40'W and 52°00'N and 50°20'N weighted according to length.
Dominant orientations are :
1. 0-18°T (strong)
2. 27-54°T (strong)
3. 86-89°T (weak)

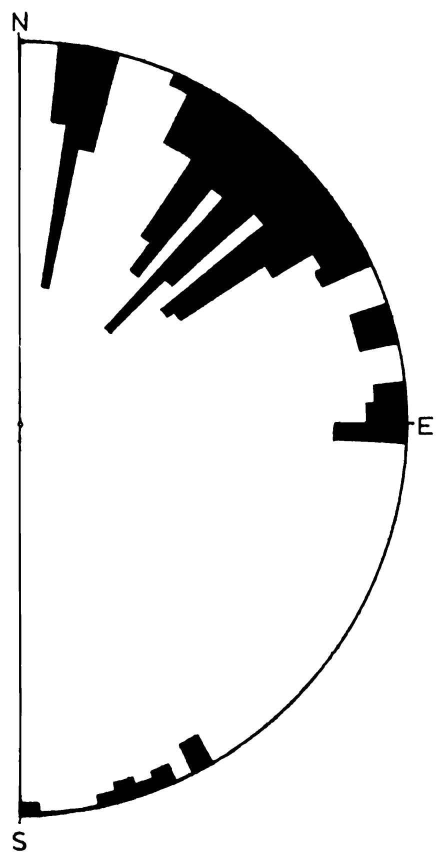


Fig. 138 - Rose diagram of linears within the map-area weighted according to length.
Dominant orientations are :
1. 6-15°T (strong)
2. 27-60°T (strong)
3. 90-93°T (weak)

linear valleys in the map area, fig.138. In each diagram the linears are weighted according to length. It is evident that three dominant sets of linears exist striking N to NNE, NE, and E respectively. The same three sets are common to the Gulf of St.Lawrence as a whole.

Linear valleys within the area that are occupied by major faults have a sinistral displacement and most strike NE. A prominant N to NNE-striking linear valley is occupied by a giant gabbro dyke. Other similar dykes have the same strike but are not topographic lows. The N to NNE tension joint appears for the first time and may be considered a relaxation tension joint. Kranck (1965) suggested that it is a tension fracture resulting from movement on the NE Petit Rigolet fault. Assuming the linear valleys to represent related structures, and assuming that the faults are vertical, the movement picture and stress relations are as shown in fig.139. The over-all movement of material is parallel to the minimum stress direction which is in general the same as that shown by Kumarapeli and Saull(1966, fig.4) for the movement of Newfoundland.

Orientation of the younger dykes is related to the over-all joint system in Ordovician times. It is interesting to note that the younger dykes cutting the central portion of the Mutton Bay pluton have the same pattern as the syenite's satellitic dykes, indicating the presence of an older system on which a younger system is superimposed.

Joints

Joints in the metamorphic rocks

The area is divided into eight metamorphic domains, partly on lithologic grounds and partly

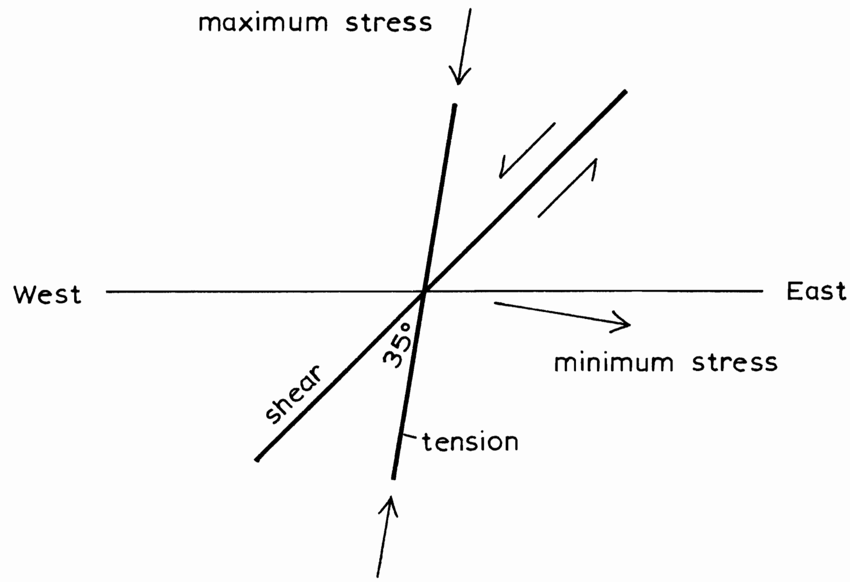


Fig. 139 - Relation between the NE sinistral faults (shear fractures) and the tension fractures occupied by the giant gabbro dykes. Orientations are taken from the Rose diagram of linears within the map area (fig.138).

on position with respect to the syenite pluton. The domains are outlined in fig.140. Contour diagrams of joints for each domain are presented in figs.141 and 142.

A study of the contour diagrams shows that there are essentially two pairs of mutually perpendicular vertical sets of joints. One pair strikes N 15°W and N 75°E and the other N 15°E and N 75°W. One, or the other, or sets from both pairs are found in a single projection. There is a systematic variation on passing from one side of the syenite pluton to the other, suggesting that the syenite pluton has affected the jointing in the gneisses. The NE and NW sets are present but are not as well developed. The early E-W set is not distinguished from

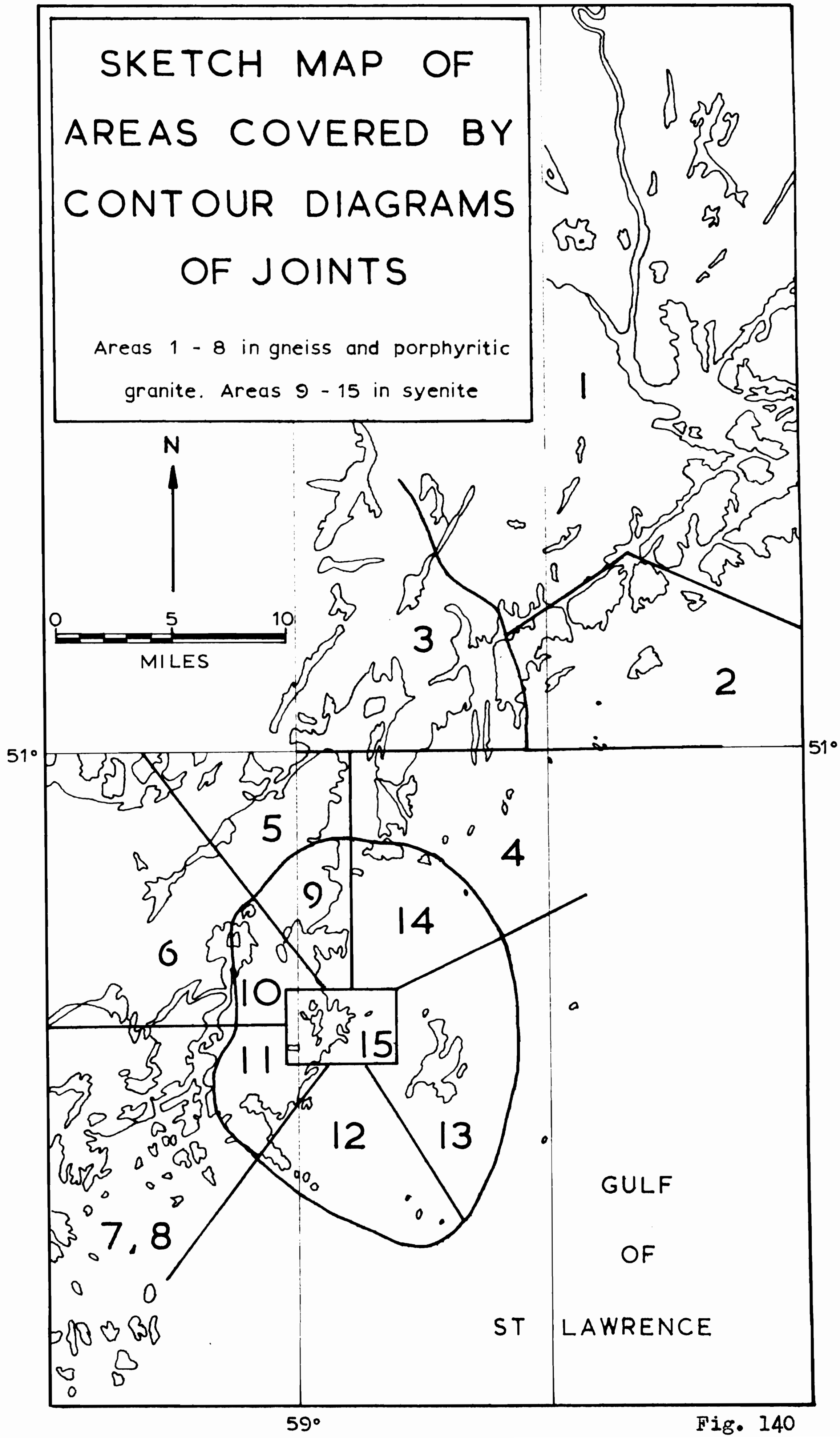
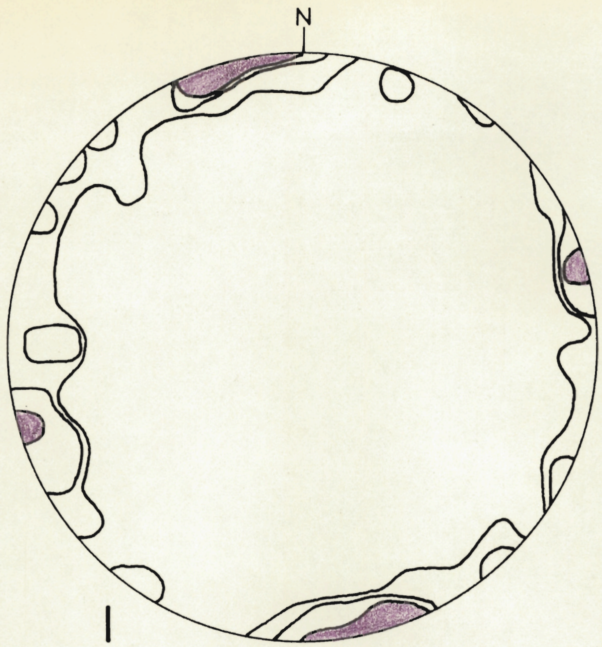
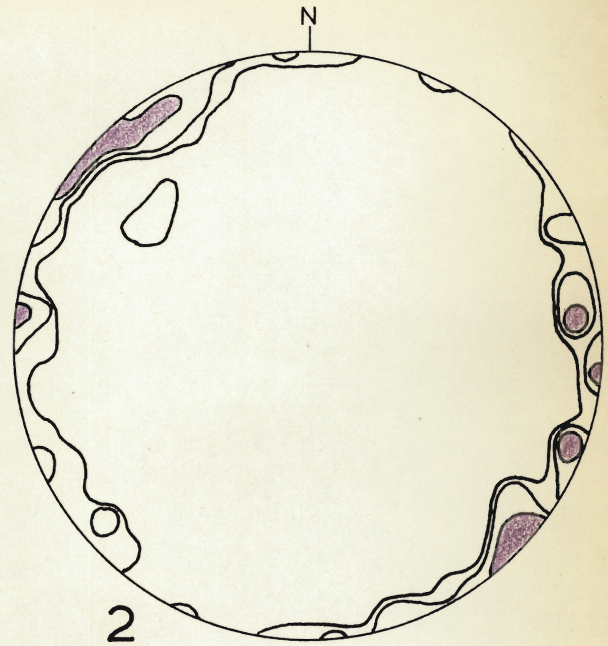

SKETCH MAP OF
AREAS COVERED BY
CONTOUR DIAGRAMS
OF JOINTS
Areas 1 - 8 in gneiss and porphyritic
granite. Areas 9 - 15 in syenite
N
0
5
10
MILES
51°
51°
59°
1
2
3
4
5
6
7, 8
9
10
11
12
13
14
15
GULF
OF
ST LAWRENCE

Fig. 140



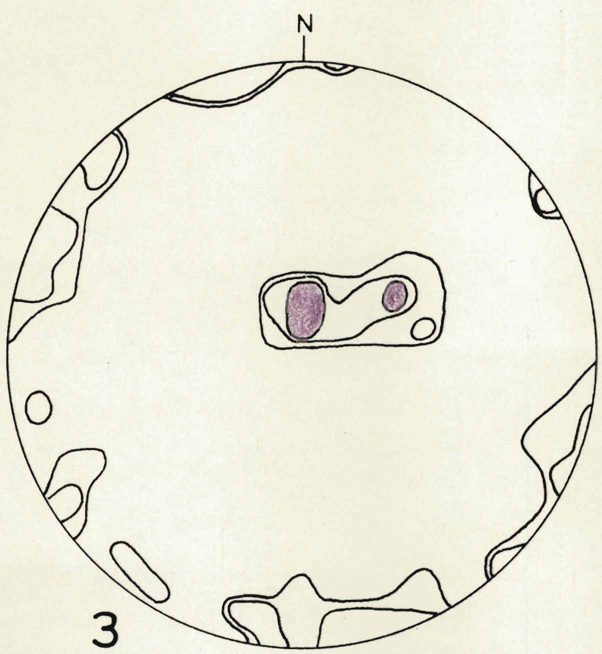
520 poles to joints

Contours: 2, 3, 4% per 1% area



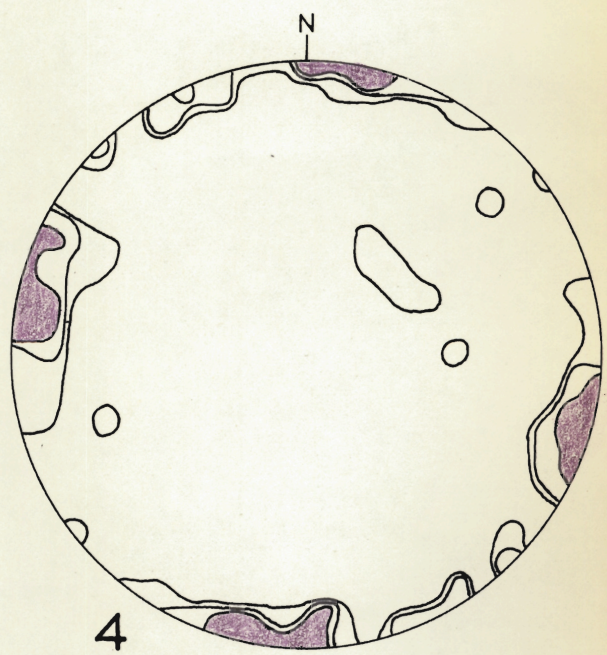
92 poles to joints

Contours: 2, 3, 4% per 1% area



260 poles to joints

Contours: 2, 3, 4% per 1% area



83 poles to joints

Contours: 2, 3, 5% per 1% area

Fig. 141 - Contoured upper hemisphere equal area projections of poles to joints in areas 1-4 in fig.140, p.280.

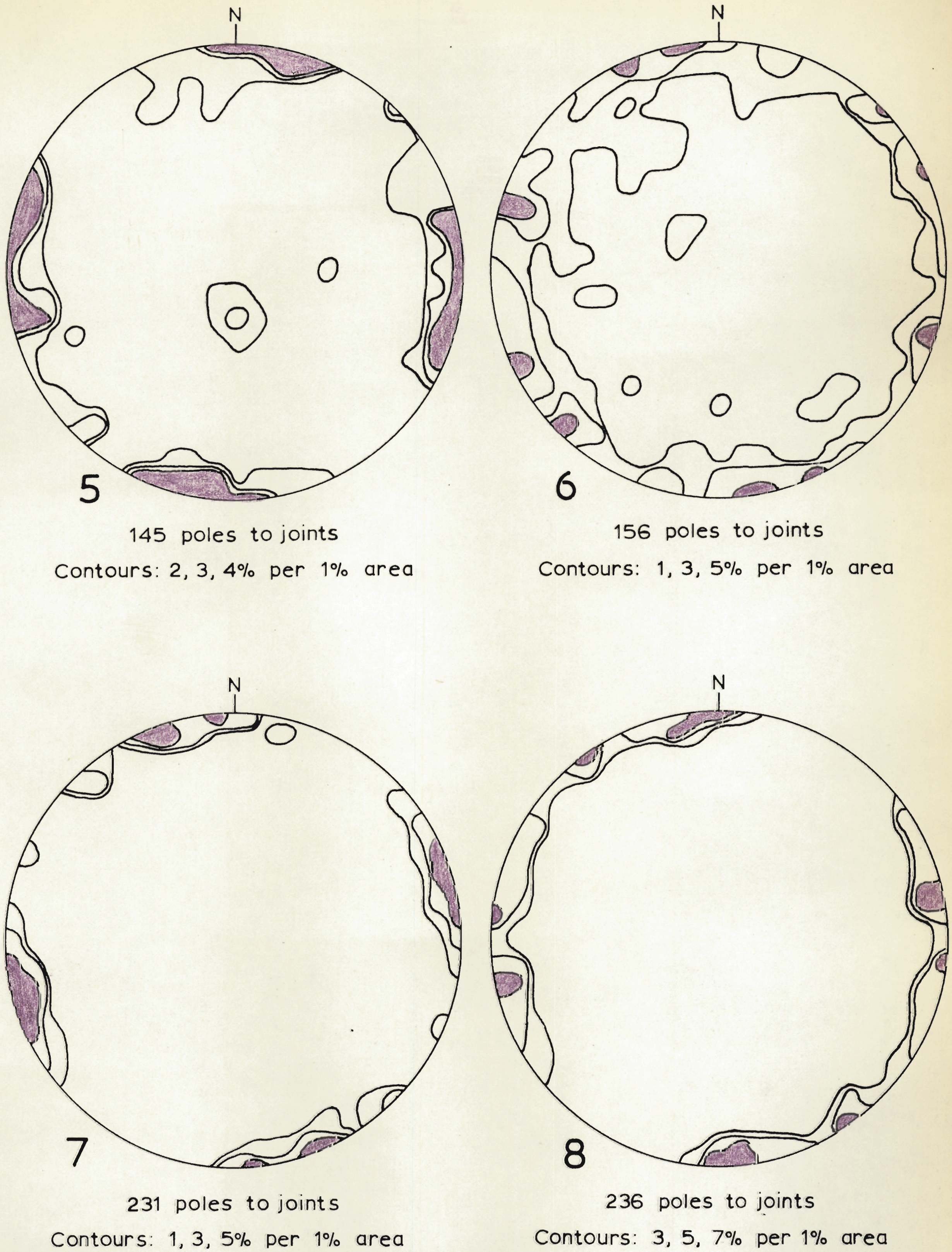


Fig. 142 - Contoured upper hemisphere equal area projections of poles to joints in areas 5-8 in fig.140, p.280.

the N 75°W and N 75°E sets. Joints parallel to foliations are common but were not plotted to avoid confusion.

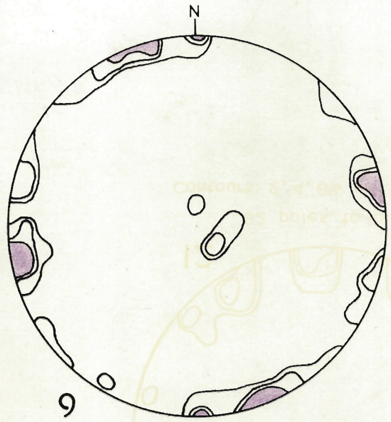
It may be assumed that the most northerly domain (No.1, fig. 141) has been the least affected by the pluton and that the pair of joint sets striking N 15°W and N 75°E are the regional pair.

Joints in the Mutton Bay syenite

Joints were measured in the syenite pluton with as even a distribution as possible. The pluton is divided into seven domains (fig.140) and for each a contour diagram of joints is presented (fig.143).

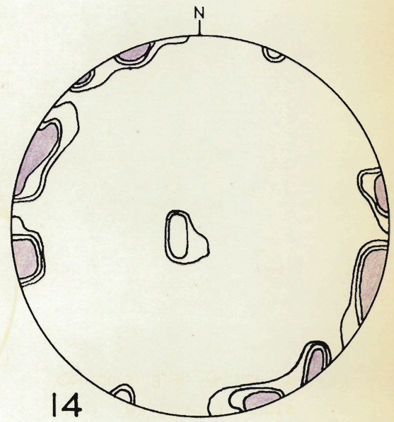
Vertical joints show no apparent relation to the contacts of the pluton whereas horizontal joints do. This is clearly shown in contour diagrams of domains 9, 12, 13, and 14 (fig.143). Contour diagrams of domains 10, 11, and 15 show maxima of horizontal joints at lower contour levels than those shown. Contour diagram of the core shows a weak maximum at the centre at a 1-2 percent contour level. The horizontal jointing dips at shallow angles towards the contacts. Since the syenite is a topographic high, this may be sheeting resulting from removal of load.

Degree of development of the vertical joint sets varies from domain to domain. While a set may be regional, its greater or lesser development appears dependent on its location within the pluton. NE and N 75°E sets dominate in all domains. They parallel the dominant regional trend in the area. The E-W set is present in most domains. The N 15°E and N 15°W sets are not developed in the south but are conspicuous elsewhere. The NW set is not developed northeast of the pluton.



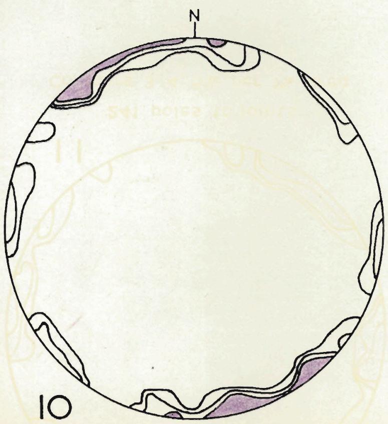
9

161 poles to joints
Contours: 3, 4, 5% per 1% area



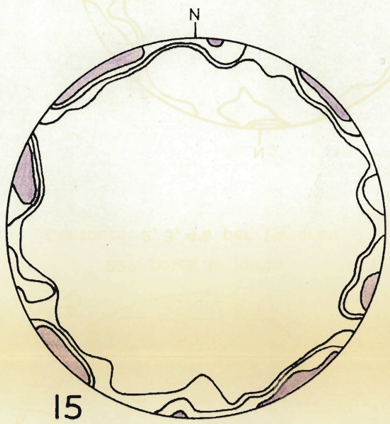
14

137 poles to joints
Contours: 3, 4, 5% per 1% area



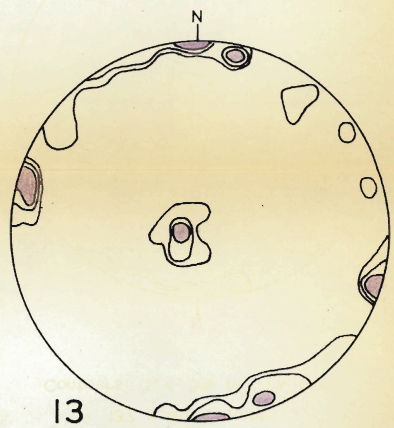
10

183 poles to joints
Contours: 3, 4, 5% per 1% area



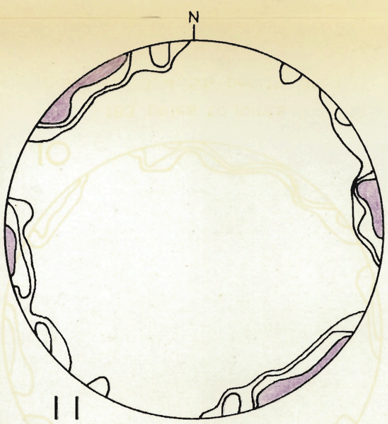
15

227 poles to joints
Contours: 2, 3, 4% per 1% area



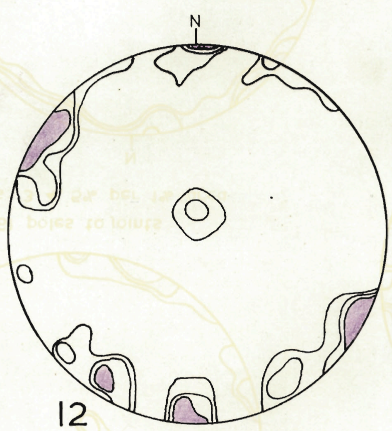
13

83 poles to joints
Contours: 3, 4, 5% per 1% area



11

241 poles to joints
Contours: 3, 4, 5% per 1% area



12

62 poles to joints
Contours: 2, 4, 6% per 1% area

Fig. 143 - Contoured upper hemisphere equal area projections of poles to joints in areas 9 - 15 of fig. 140, p. 280

Comparison of joints in metamorphic and igneous rocks

The joints in the syenite pluton, when compared with the joints in the gneisses surrounding it, show that some joints are penetrating and others not. Fig.144 shows the distribution of joint sets among the domains both in the metamorphic and igneous rocks. E-W and NS sets are not included as they are not easily distinguished from the N 75^{o}W and N 75^{o}E and the N 15^{o}E and N 15^{o}W sets respectively.

The early mutually perpendicular joint sets, NE and NW, are best developed in the syenite, particularly at the core. In the gneisses the set perpendicular to the pluton is the one developed. The latter would be a tension joint caused by the outward push of the syenite. The early E-W set is present but is often continuous with the N 75^{o}W and N 75^{o}E sets.

The two sets that are most penetrative are the two oriented closest to two of the three major fracture systems of the region, N 15^{o}E and N 75^{o}E. The N 15^{o}E set is probably related to the movement on the NE faults and is a fracture cleavage or relaxation tension joint. The N 75^{o}E set is close to the original E-W tension fractures.

A joint set that might also be considered penetrative is the N 15^{o}W set. This is present on the Rose diagram of topographic linears within the map area as a weak concentration. This is also the trend of much of the foliation, so it is possible that some N 15^{o}W linears representing faults have been overlooked or mistaken for those resulting from differential weathering of the gneisses. Movement appears to have taken place on the N 30^{o}E linear of

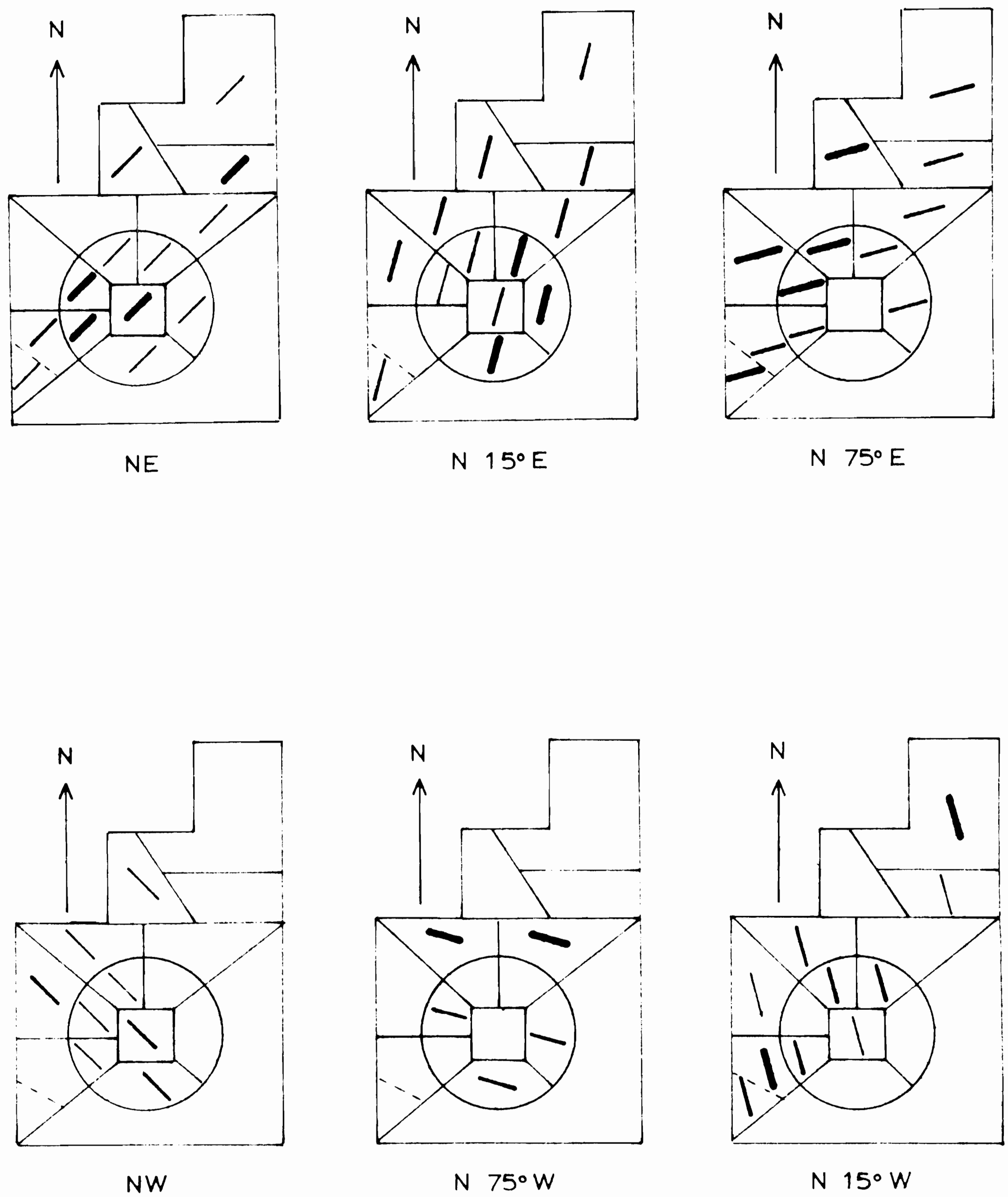


Fig. 144 - Distribution of joint sets, excluding N-S and E-W sets, plotted on a simplified version of the map of areas covered by contour diagrams (fig.140). The circle represents the Mutton Bay intrusion. The four strongest joint sets from each contour diagram (figs.141, 142, and 143) are plotted on the relevant map using lines of different thickness. The thickest line represents the strongest and the thinnest line the weakest of the four joint sets.

Kécarpoui lake. The N 15°W joints may bear the same relation to this fault as some of the N 15°E linears bear to the NE faults.

The N 75°W set does not appear to have an independent explanation. However, mutually perpendicular joint sets are common in more massive rocks and this set would exist simply because the N 15°E set exists. This may also be the explanation for the N 75°E set. Once one joint set exists, changed stress conditions will resolve themselves to accomodate the existing joints as well as adding others.

Conclusions

It must be concluded that the NE, NW, E-W, and N-S joints were inherited from pre-syenite time. After intrusion of the syenite pluton faulting occurred which followed the early NE joint sets. Faulting produced the N 15°E joints and secondary faulting along some of these produced the N 15°W joints. Under suitable stress conditions mutually perpendicular sets to the N 15°E and N 15°W sets would form. These might however be in part related to the pre-existing well developed E-W set which has a sufficient spread of orientation.

In the development of joints pre-existing joints play an important part. A new set will not develop if a suitably oriented one is already present.

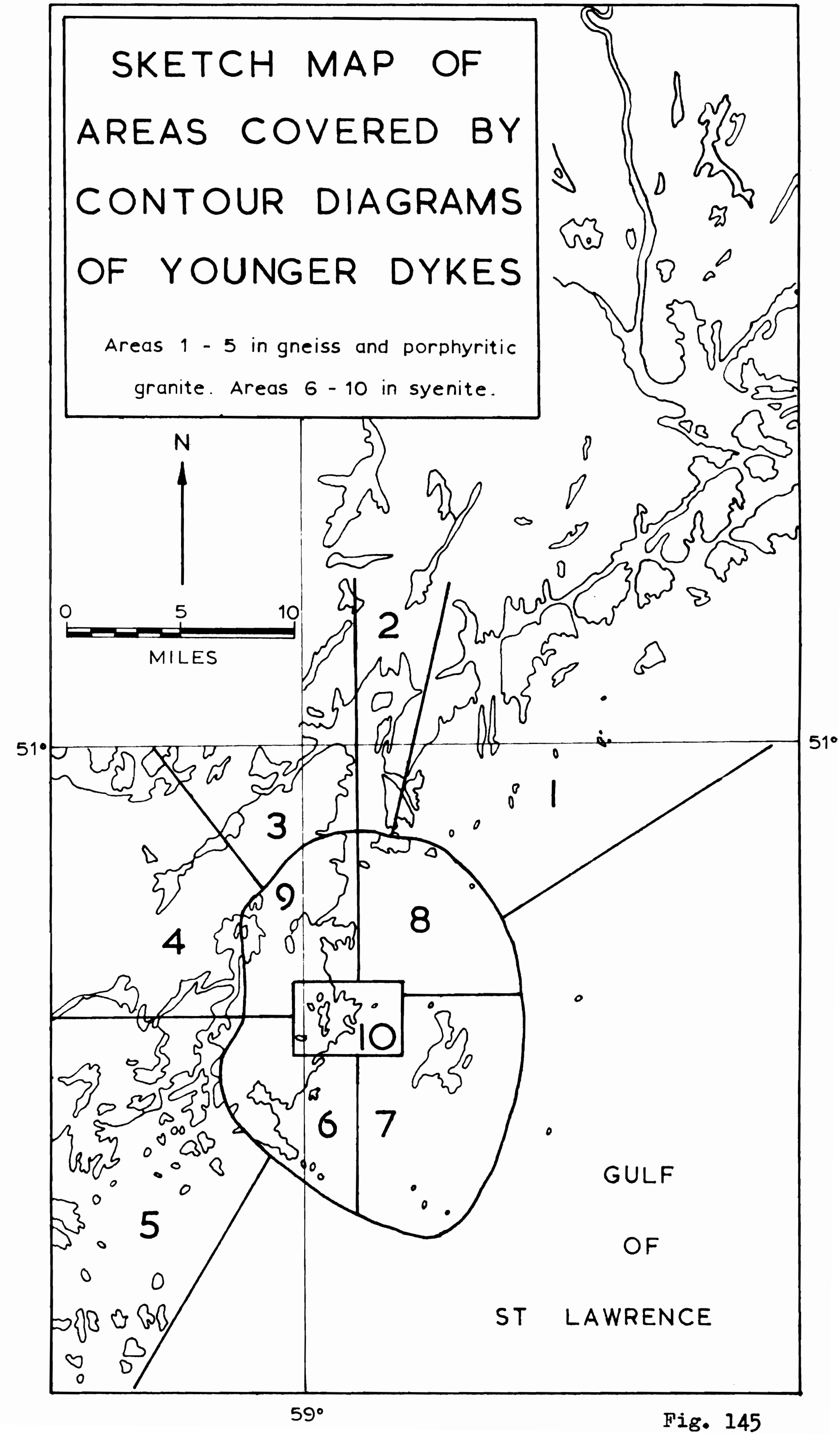
The Mutton Bay pluton has strongly influenced the development of various joint sets. The NE and NW sets were probably affected most by the intrusion of the syenite. The variation in development of the remaining joint sets is believed the result of changed stress conditions caused by the syenite mass in the gneiss.

The porphyritic granite also appears to have affected the development of certain joints. The strong development of the N 15°W and N 75°E sets in the two gneissic domains, No.1, fig.141 and No.7, fig.142, and the stronger development of other sets in domain No.8, fig.142, in porphyritic granite adjacent to domain No.7, fig. 142, and in the dominantly porphyritic granite domain, No.2, fig.141, adjacent domain No.1, fig.141, indicates that new joints might have more difficulty in forming in gneisses than in more massive granite. Foliation joints in the gneisses may absorb much of the stress.

Orientation of younger dykes

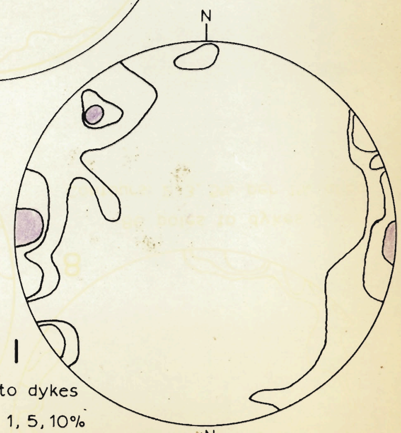
The area is divided into 10 domains (fig.145) and for each a contour diagram of younger dykes is prepared and presented in fig.146. A comparison of the orientation of joints with that of the younger dykes shows that only certain of the joints are occupied by dykes, and these vary according to their position with respect to the syenite pluton. The dykes are not related temporally to the syenite but they are related structurally.

Fig.147 shows that dykes in the NW occupy N to NW joint sets even though they are not the dominant joint sets in the area. In the northeast and southwest dykes occupy the penetrative N 15°E to N 75°E joint sets. In general the dykes strike perpendicular to the contact of the syenite, occupying those joints which are nearly perpendicular to the contacts and dilated the most. The two dyke sets, NE and NW, strongly developed in the core of the syenite, represent the very early joint sets.

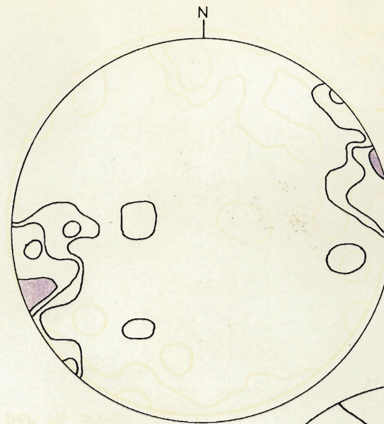


SKETCH MAP OF AREAS COVERED BY CONTOUR DIAGRAMS OF YOUNGER DYKES
Areas 1 - 5 in gneiss and porphyritic granite. Areas 6 - 10 in syenite.
N
0
5
10
MILES
51°
51°
1
2
3
4
5
6
7
8
9
10
GULF
OF
ST LAWRENCE
59°

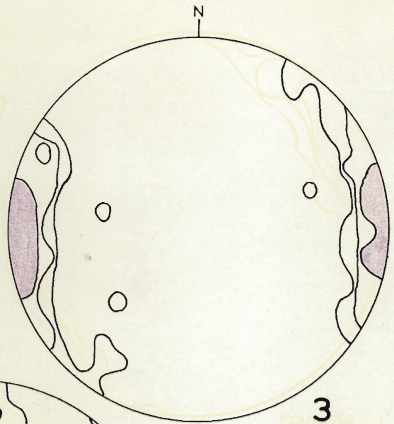
Fig. 145



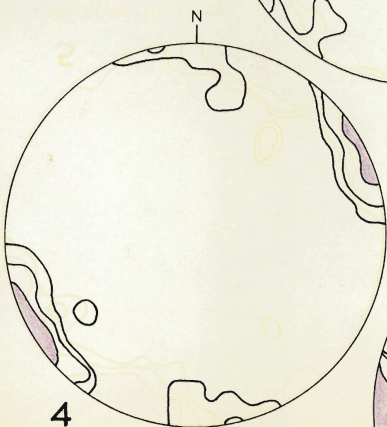
1
118 poles to dykes
Contours: 1, 5, 10% per 1% area



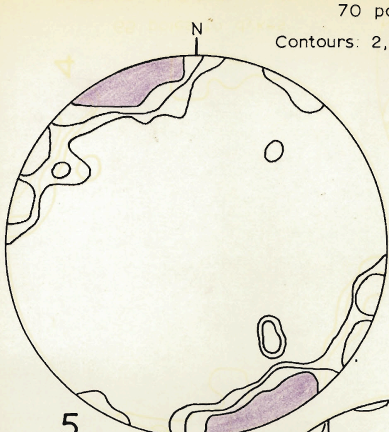
2
23 poles to dykes
Contours: 1, 4, 12% per 1% area



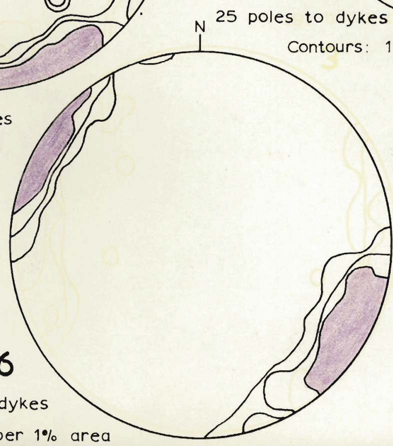
3
181 poles to dykes
Contours. 1, 3, 7% per 1% area



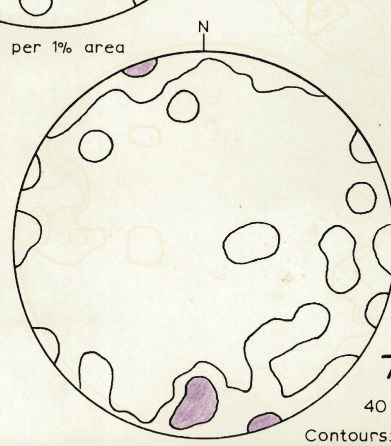
4
65 poles to dykes
Contours: 4, 7, 10% per 1% area



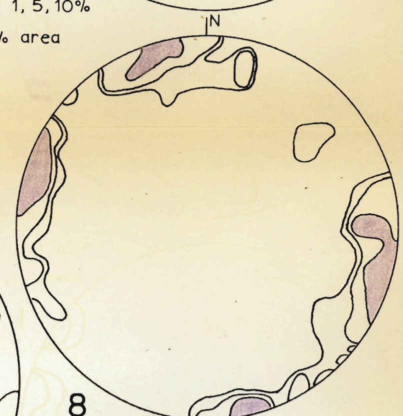
5
88 poles to dykes
Contours: 2, 3, 5% per 1% area



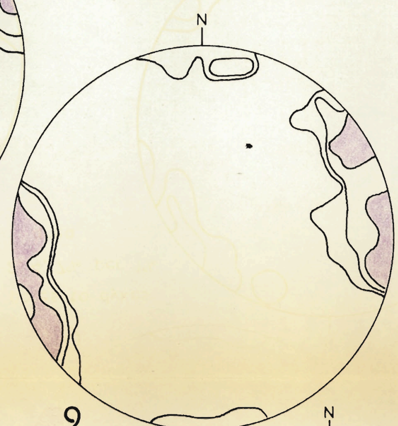
6
224 poles to dykes
Contours: 2, 3, 5% per 1% area



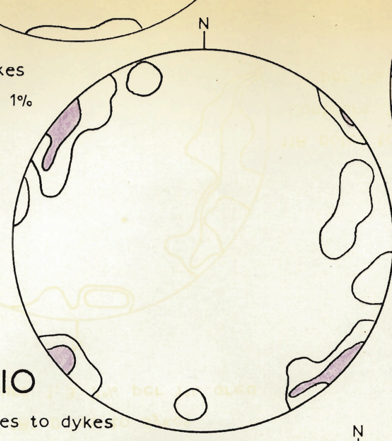
7
40 poles to dykes
Contours: 1, 2% per 1% area



8
86 poles to dykes
Contours: 2, 3, 5% per 1% area



9
70 poles to dykes
Contours: 2, 4, 7% per 1% area



10
25 poles to dykes
Contours: 1, 3% per 1% area

Fig. 146 - Contoured upper hemisphere equal area projections of poles to dykes in areas 1 - 10 of fig. 145, p. 289

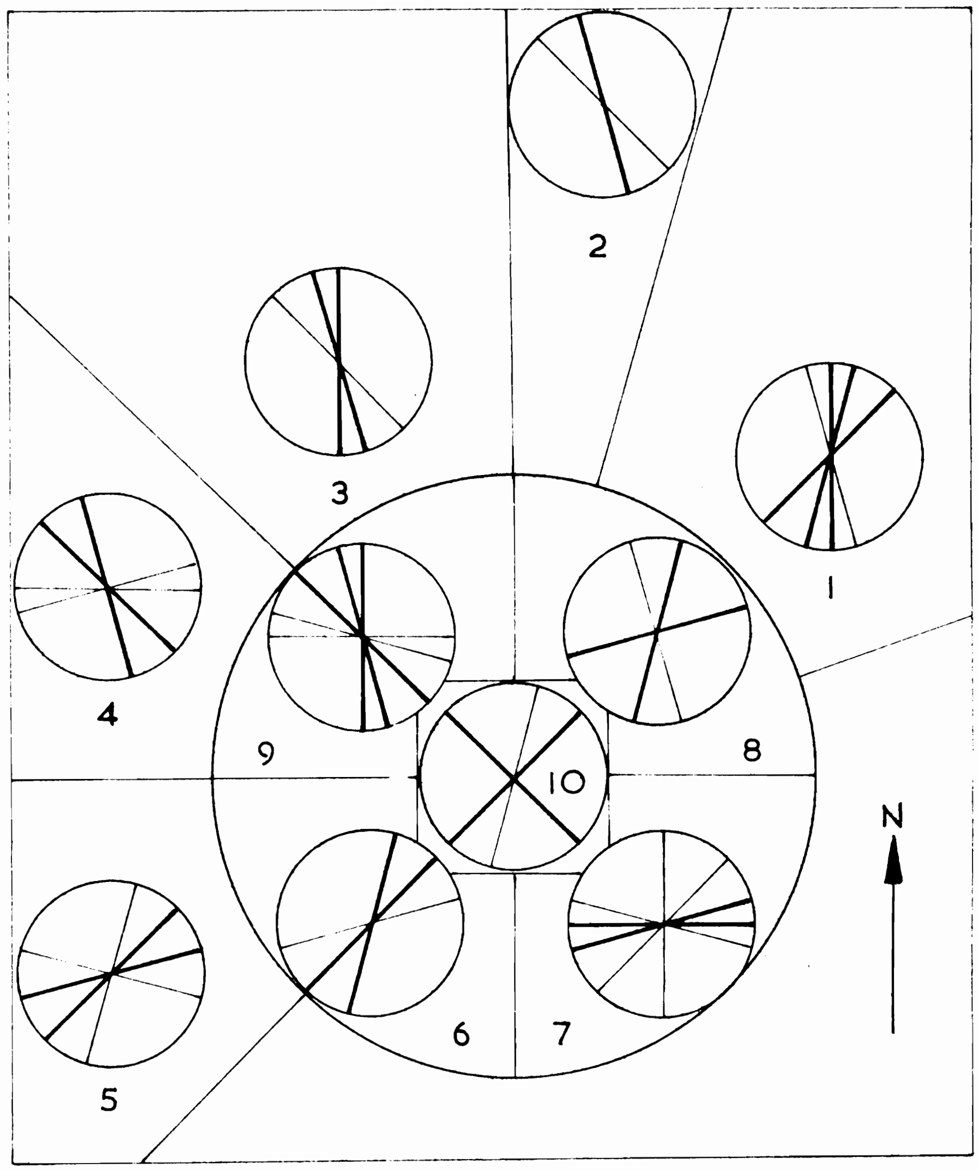


Fig. 147 - Orientation of the Younger Dykes on a simplified version of the map showing the areas covered by contour diagrams (fig.145, p.289). The circle represents the Mutton Bay intrusion. Dominant orientation taken from the contour diagrams (fig.146, p.290) are marked with thick lines and weak orientations with thin lines. Numbers refer to areas in fig.145 (p.289) and to contour diagrams in fig.146 (p.290).

STRUCTURE OF THE DYKES

Dykes are miniature intrusions and their structures are just as important indicators of physical conditions prevailing at the time of intrusion as are the structures of larger intrusives.

Flow phenomena

Flow differentiation occurs in dykes once the solid phases start to crystallize, and differentiation processes that occur in flowing crystal mushes must be considered. Principles and experimental models of flow differentiation are given by Bhattacharji and Smith (1964), and have been discussed earlier (p.178). The strongest differential flow in a moving magma is at its contacts, and results in preferred orientation of crystals and a fine grain size at the contacts, which is the case in all unmetamorphosed dykes of the area.

Effectiveness of flow differentiation is demonstrated by dykes containing inclusions in their centres (fig.148). It is also clearly demonstrated by a narrow trachyte dyke containing numerous plagioclase xenocrysts plucked from gabbro country rock (fig.149). In the contact zones the felspar xenocrysts are parallel to the contacts but lie oblique to the contacts on approaching the centre, and show the greatest random orientation in the centre. The contacts are relatively free of xenocrysts and the size of xenocrysts decreases towards the contacts. The same distribution of size, orientation, and number of xenocrysts (or phenocrysts) is common to many dykes containing xenocrysts (or phenocrysts). Three dykes were studied in detail and fig. 150 shows the variation in orientation and number of 'crysts' across one of these dykes which is typical of most dykes in the area.

Fig. 148 - A 5-foot wide diabase dyke with fine-grained contacts (12-15 inches wide) and a central portion containing small felspar phenocrysts or xenocrysts. Angular inclusions of the gneissic country rock are concentrated in a 1-foot wide zone in the centre of the dyke. Bayonet structure is seen in the background.

Fig. 149 - An olive black to dusky yellowish brown trachyte dyke containing numerous plagioclase xenocrysts plucked from the gabbro country rock and which increase in number towards the centre of the dyke. Xenocrysts are oriented parallel to the contacts in the contact zones but have a random orientation in the centre of the dyke.

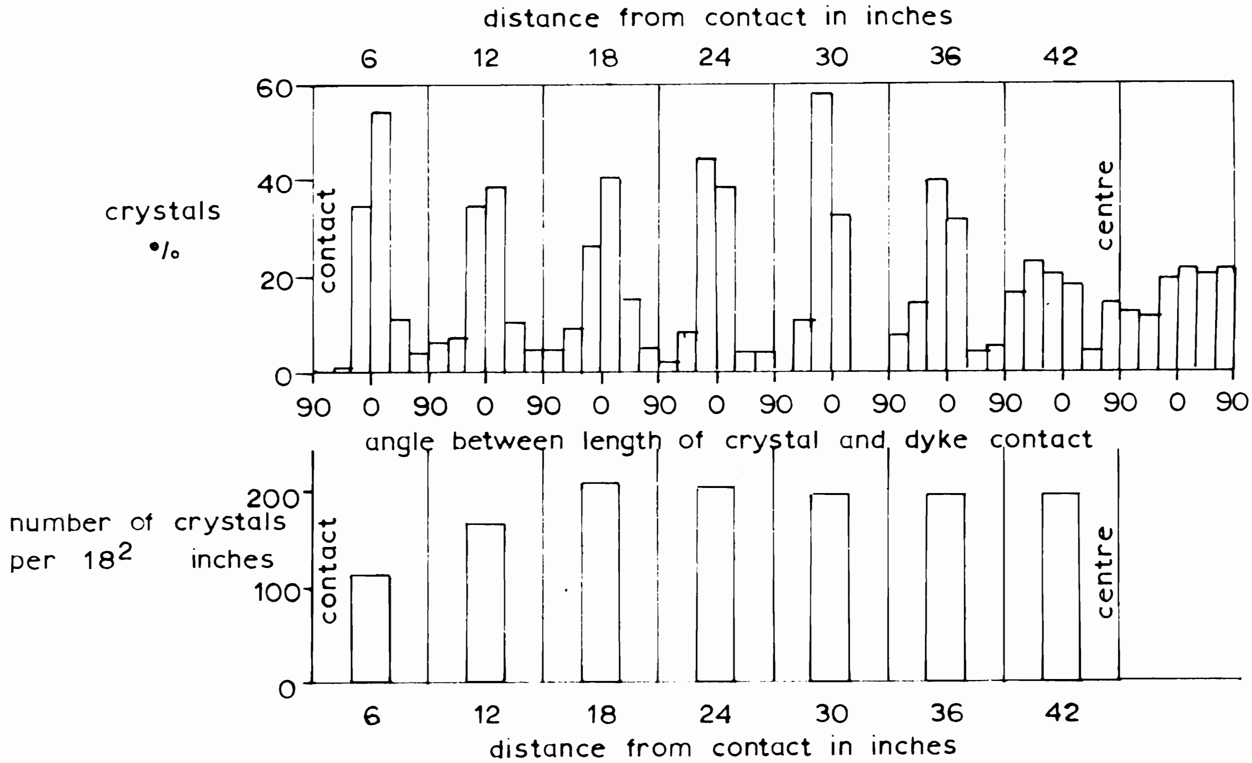


Fig. 150 - Variation in the orientation (above) and number (below) of phenocrysts or xenocrysts per unit area from the contact to the centre of a 7½-feet wide moderate reddish orange trachyte dyke. The percentage of oriented crystals 0–30°, 30–60°, and 60–90° to the dyke contacts in both a positive and negative sense are plotted as a histogram for each unit area.

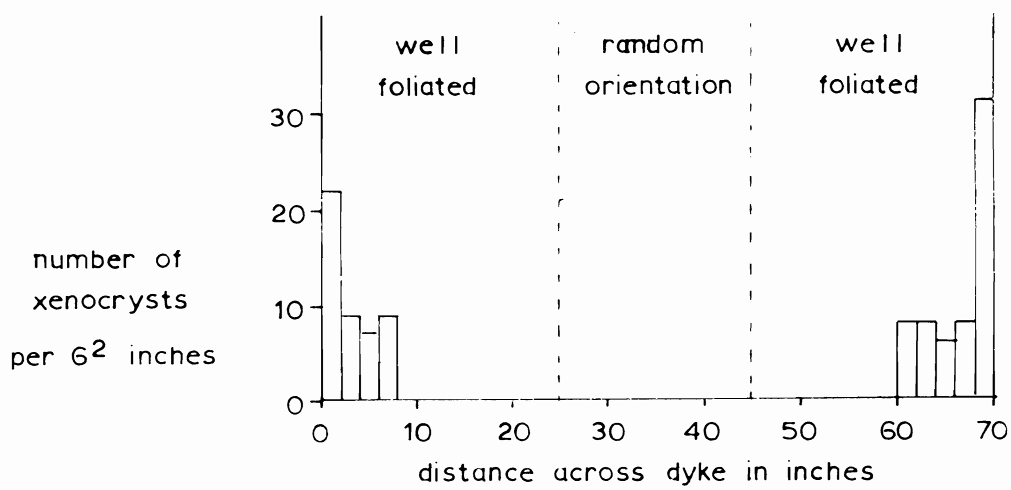


Fig. 151 - Variation in the number of xenocrysts at 2-inch intervals across a 70-inch pale red trachyte dyke.

There are exceptions and a number of xenocrysts in a 70-inches wide trachyte dyke varied as shown in fig.151. The xenocrysts are clearly related to the wall rock but the supply was apparently cut off by solidification of the magma at the contacts. Another exception is a 20-feet wide moderate reddish orange trachyte dyke containing three kinds of 'crysts' having different sizes and colour, the one variety being definitely xenocrysts. Each of the 'crysts' has its own distribution and all three are superimposed. Grey 'xenocrysts' and a few inclusions are found in a zone half-way between the contact and centre. Red 'crysts', > 1/2 inch in diameter, show the normal distribution as in fig.150 (p.294), and half-inch diameter red 'crysts' represent the start of a third distribution in which a fresh supply of 'crysts' is starting to move towards the centre and has a distribution like that shown in fig.151 (p.294).

The distribution of number, size, and orientation of 'crysts' is important in that it can be explained easily by flow differentiation, but only in some cases by chilling. Both flow differentiation and chilling explain the normal distribution of phenocrysts, but chilling cannot explain the distribution of xenocrysts and, if xenocrysts are affected by flow differentiation, then phenocrysts are also affected. It is important to consider the effects of flow differentiation before other processes when a flowing crystal mush is involved.

<u>Width of dykes</u>

The widths of all straight-walled dykes observed were recorded and the number of dykes is plotted as histograms against average width to the nearest foot in fig.152a-d. The

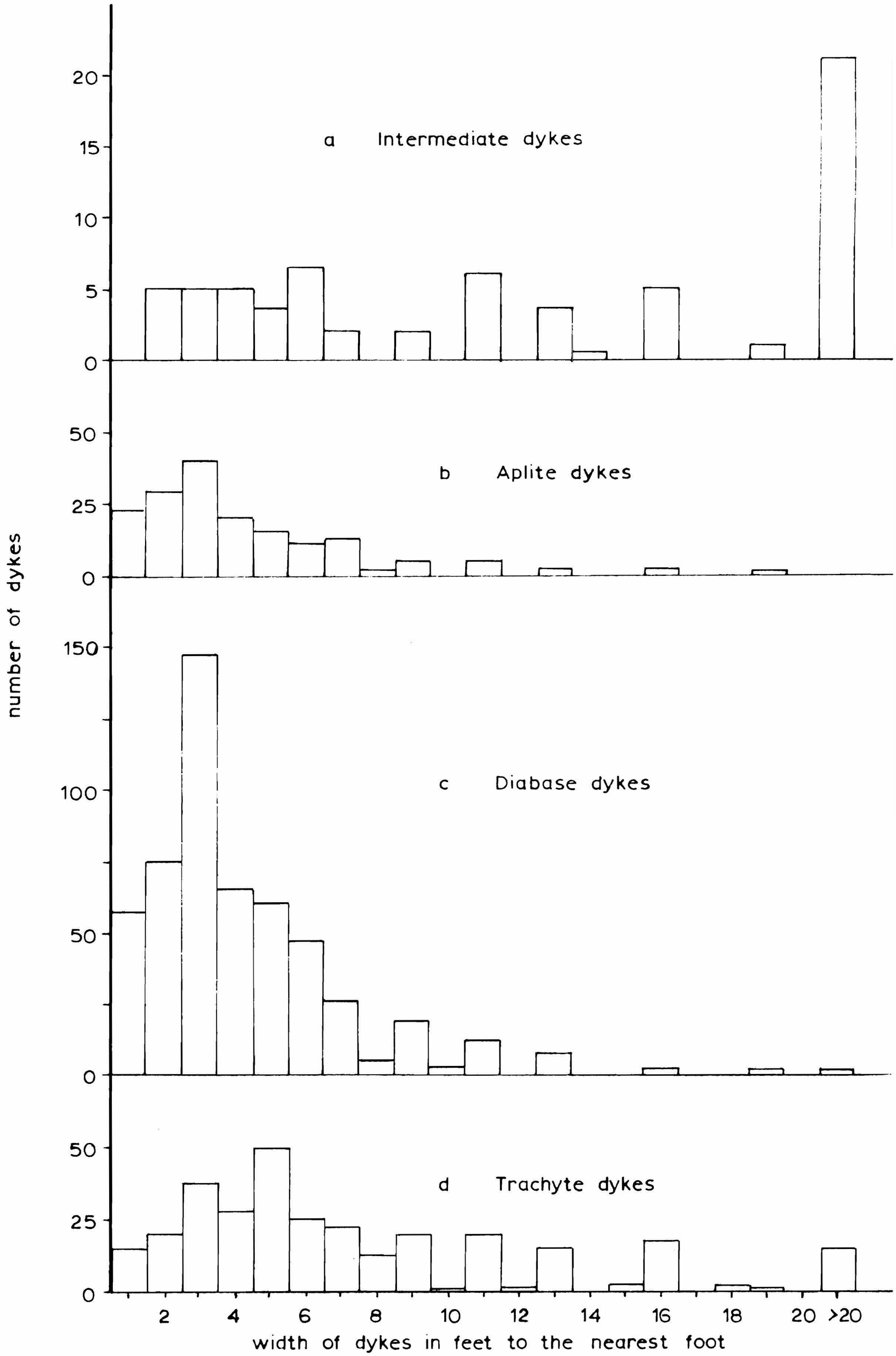


Fig. 152 - Variation in width to the nearest foot of dyke suites in the area.

dykes are divided into four groups, the metamorphosed intermediate dykes, pink and grey aplites related to the syenite pluton, diabases, and trachytes, the latter two believed related to the giant gabbro dykes.

A preliminary study showed no difference in width between red and brown trachyte dykes, nor between pink and grey aplites. There is no difference between the width of dykes cutting the syenite and equivalent dykes cutting the gneiss. Early basic lamprophyres and late hornblende lamprophyres have the same size distribution as the diabases and aplites but occur in insufficient number to warrant plotting.

Many intermediate dykes are 1-6 feet wide with no marked maximum and there are many greater than 10 feet and up to 75 feet wide (fig. 152a, p.296). There is no favourable width, suggesting that the amount of magma intruded depends mainly on the space available rather than on factors like viscosity of magma. Emplacement of the dykes was at great depths where cooling was slow and there would be a greater tendency for dykes to expand laterally than if they were emplaced near the surface.

Pink and grey aplites are mostly less than 10 feet wide with a maximum near 2 feet (fig.152b, p.296). The dykes filled fractures, formed in the cooling Mutton Bay intrusion, that were evenly distributed and of uniform size.

Trachyte and diabase dykes are believed to have intruded under the same temperature, pressure, and depth conditions, and differences in size must be related to composition. Diabase dykes are narrower than the trachytes and show a strong maximum at 2 feet whereas the trachytes show weak maxima at 2 feet and 4 feet. It is well-known that basic lavas have a lower viscosity than acidic lavas, and viscous magma will push laterally more than a fluid one and so tend to be wider. High carbonate content probably coupled with high volatiles may lower the viscosity in some trachyte dykes. The two maxima in fig.152d (p.296) are believed to have resulted from magmas of two viscosities, depending on whether the volatiles escaped from the magmas or not. The aplite dykes, with a maximum at 2 feet, intruded at a greater depth and higher temperature than the trachytes and filled fractures in the Mutton Bay intrusion that need not have reached the surface. The volatile content would be more readily retained under these conditions and the magma remain fluid.

Characteristic variations in width are found for each of the dyke suites. They offer a means of grouping dykes whose age relations are not known and of determining some physical conditions of intrusion when other factors are known. Dykes of similar composition have similar widths under similar physical conditions, but different widths under different physical conditions.

Jointing in dykes

Development of joints in dykes varies with composition. In basic dykes the jointing is developed parallel and perpendicular to the contacts. Joints perpendicular to the contacts (fig.153) have been ascribed to cooling and are a less spectacular development of polygonal jointing found in basalt flows. It is interesting that the jointing in the carbonatized dykes at the bottom of Baie des Ha! Ha! is also perpendicular to the contacts.

Characteristic of felsic dykes are mutually perpendicular sets

Fig. 153 - Diabase dyke cutting gneiss and showing typical jointing perpendicular to the contacts.

Fig. 154 - A 5-foot wide grey aplite dyke, cutting syenite, with a zone of inclusions (1-foot wide) in its centre. Mutually perpendicular joints intersecting the contacts at 45° are present in addition to joints perpendicular to the contacts.

Fig. 155 - Contrasted jointing in two adjacent trachyte dykes cutting syenite and separated by a thin slice of country rock. The dyke on the right with closely spaced jointing parallel to the contacts has a well-developed trachytoidal texture.

of joints intersecting at the contacts at angles of about 45° (fig.154). Joints perpendicular to the contacts are poorly developed. Characteristic of many, but not all, trachyte dykes is closely spaced jointing parallel to the contacts (fig.155) and this is present where the dyke has been weathered by wave action. It appears related to a well-developed trachytoidal texture.

The oblique jointing cannot be due to the simple cooling which caused jointing perpendicular to the walls of the basic dykes. Cooling joints result from contraction and it is possible that basic dykes shrink more than the felsic dykes. The oblique jointing may be secondary, developed in the crystallized tabular body by stresses in the country rock. Stresses that formed the tension joint, if maintained after the dyke crystallized, might create shear joints in the dyke.

ECONOMIC GEOLOGY

The economic geology of the region is described by Hale (1962) who believes the most likely sources of economic mineralization are the gabbro and anorthosite masses occurring on Mécatina river to the west and at Old Fort lake and Lobster Bay to the east. In the latter body sulphides occur at the contact with the gneisses and are described by Longley (1944b). Longley's (1944b) description of the rock matches the meta-gabbros of the Mutton Bay area.

Sulphides

Three ages of sulphide mineralization are apparent in the area. The earliest phase carries iron and copper with minor amounts of lead, zinc, and nickel. Traces of gold and silver are associated. Pyrrhotite, pyrite, chalcopyrite, and rare molybdenite occur in meta-gabbros and amphibolites as layered zones of disseminated grains or as veins. Some pyrite and chalcopyrite were also observed in calc-silicate rocks and pyrite is common in graphite-bearing sillimanite gneisses. The above sulphides, except for the veins, are apparently syngenetic with the host rock. Pyrite was also observed with fluorite in a pegmatite on Île Wakeham.

Pyrite and chalcopyrite are accessories in the syenitic rocks, but molybdenite is found around Tabatière concentrated in small riebeckite and aplite veins related to the syenite. A 2-inch wide quartz vein cutting the syenite contact south of Mutton Bay carries a little pyrrhotite.

The most recent sulphide mineralization is related to the carbonate dykes of the younger dyke group and carries lead, zinc, and silver.

Assays of the sulphide occurrences have been published (Davies, 1963, 1965a, 1965b).

Discussion : The age of mineralization is important in evaluating the mineral potential of the area. Copper-nickel deposits should be sought in the gabbroic rocks of Precambrian age and especially in moderate to shallow-dipping layered bodies. Molybdenite will be concentrated in and near the syenite pluton. The lead mineralization is the most interesting as it is associated with dykes, probably of Ordovician age, that were not deeply buried. Erosion is not likely to have removed all possible orebodies that might have formed. Lead ore deposition is very possible at depth and targets might be suitable trap rocks and fault zones which the carbonate dykes frequently occupy.

Black sands

Weathering of gabbros, meta-gabbros, and amphibolites gives rise to concentrations of black sands in many lakes. Minor concentrations occur also in the sands of Rivière St-Augustin and in the few marine beaches. Clark and Hale (1962) studied the heavy mineral sands from the Old Fort area and found a close correlation between the mineral content of the sands and of the local bedrock. Assays for Sn on 15 heavy mineral concentrates gave values between 0.001 and 0.002 percent.

Sand and gravel

Large deposits of sand and gravel are relatively scarce and non-existent in some parts of the area.

PROBABLE GEOLOGICAL HISTORY OF THE AREA

1. Deposition in a geosynclinal basin, before 1600 m.y., of a sequence of greywackes and shales with minor intercalated impure limestones, quartzites, and possibly basic volcanics, to a minimum thickness of 30,000 feet, and probably overlain by a minimum of 25,000 feet of pure quartzites (Wakeham series).

2. Folding about a north-south axis and intrusion of diapiric granite accompanied by regional metamorphism, probably for the first time at about 1600 m.y. and perhaps repeated again at about 1000 m.y. Emplacement of basic sills and dykes some of which have pyrrhotite segregations. During one or the other metamorphic event the lower part of the sequence, buried at a depth of 7-12 km., reached the upper amphibolite and lower granulite metamorphic facies, and the upper part of the sequence (Wakeham series) the epidote-amphibolite facies. Metamorphism at about 1000 m.y. was sufficiently intense to re-set the K/Ar and Rb/Sr 'clocks'.

3. Fracturing in the gneisses and the development of a joint system after the major metamorphic event.

4. Emplacement of small basic, intermediate, and acid intrusives, probably in the above order, under conditions that did not favour the formation of chill contacts.

5. Albitization and sericitization of plagioclase under low grade or autometamorphic conditions.

6. Major faulting suggested by the occurrence of numerous small faults some of which cut intermediate dykes.

7. Renewed faulting and igneous activity with intrusion of the Mutton Bay pluton at about 631 m.y. into a cover of about 9.5-13 km. (6-8 miles) above the present level. This suggests that there might have been a thickening of the sedimentary pile after the upper amphibolite - lower granulite facies metamorphism. Molybdenite mineralization accompanied the syenite intrusion. Igneous intrusion was accompanied by major faulting and the St.Lawrence rift system may have developed at this stage.

8. Erosion in the 100 m.y. preceding the Cambrian removed at least 9.5-13 km. of rock, resulting in a topography much like that today.

9. Deposition of Early Paleozoic sediments.

10. Faulting and a period of volcanic activity with intrusion of gabbro, diabase, and trachytes as dykes and probably flows at about 470 m.y. Lead mineralization occurred at this time. Faulting occurred again after intrusion of the dykes.

11. Sedimentation followed by erosion, up to and including the Pleistocene, to expose the Precambrian land surface.

12. Deposition of a thin layer of till over the whole area and of clay in deep water. Retreat of the ice sheet left the area submerged to the 410 foot level.

13. Re-emergence of the land surface resulted in reworking of the glacial deposits, erosion of dykes, removal of glacial pavements by wave action, and deposition of reworked glacial material as beach and river terraces.

MAJOR CONTRIBUTIONS

1. A little-known part of the Grenville Province has been mapped and the sequence of geological events well established.

2. A measure of the thickness (30,000 feet) and an idea of the general stratigraphy of the gneisses has been obtained from a structural analysis of the area, and the style of folding is demonstrated on a geological profile.

3. Metamorphic mineral assemblages in the gneisses are established as belonging to the hornblende-orthopyroxene-plagioclase or biotite-clinopyroxene-almandine subfacies of the granulite facies (De Waard, 1965), and the sillimanite-almandine-orthoclase subfacies of the almandine-amphibolite facies. Depth of burial during metamorphism, estimated from the metamorphic assemblages, is 7-12 km. (4.5-7.5 miles).

4. Unmetamorphosed igneous rocks have been studied in some detail, especially the Mutton Bay intrusion. Rb/Sr ages of biotites in the Mutton Bay intrusion (631 m.y.) and the giant gabbro (470 m.y.) and K/Ar ages of biotites in the Mutton Bay intrusion (580 m.y. and 592 m.y.) are presented and correlated with similar ages from other intrusives.

5. Nine complete whole-rock analyses and sixteen partial perthite analyses of rocks of the Mutton Bay intrusion are presented, and used to confirm the field evidence that the rocks belong to a consanguineous suite. The chemical analyses confirm the optical data and field relations that also show that the intrusive suite

can be divided into three or four groups. The major elements are correlated with a variation in SiO_2 content but the volatile CO_2 ~~and S, are~~ is related to the relative age of the intrusive within a group, and S, Ba and Sr are related to the relative age of the intrusive within the whole suite rather than to composition. The halogens, Cl and F, are related to the amount of apatite in the norm. The analyses of the perthite show a clear division of the Mutton Bay suite into two groups, and permit the estimation of possible temperatures and water pressures of the magma. The felspar in the earliest intrusions must have crystallized above 1015°C and at a water pressure less than 500 bars, and in the later intrusions above 810°C and at a water pressure less than 2700 bars.

6. Gravity settling of the early mafics and flow differentiation or filter pressing of the late mafic-rich liquid are the major differentiation processes recognized. These processes are confirmed by the study of chemical and modal analyses. While the magma was essentially dry its residual liquids, which are concentrated at the contacts, were enriched in water as shown by an increase in the Mg content of biotites.

7. Inversion of orthoclase to microcline occurs in syenite rocks with a well-developed foliation, suggesting that shearing in a crystal mush was the agent causing the inversion. It has been noted, however, that the potash felspar transformation and the flow foliation may be related by resulting from a common cooling history. Crystallization in the foliated syenites, including that prior to intrusion, may have been

slower than that in the massive varieties and so enabled the inversion to take place.

8. The mode of emplacement of the intrusion is shown to involve three types of intrusion, a cylindrical plug, steep-dipping cone sheets, and shallow-dipping cone sheets. The shallow-dipping cone sheets are believed to have formed in a similar fashion to fractures in cylindrical test pieces of suitable material under compression. On this assumption the depth of the present level beneath the roof of the intrusion is calculated to be 9.5-13 km. (6-8 miles).

9. Eleven partial analyses of younger trachyte dykes show a close correlation between high carbonate content and enrichment in potash felspar, suggesting that the carbonate was present in the magma as a potash carbonate until the closing stages of crystallization, when it reacted to form orthoclase and lime-magnesium carbonate.

10. A study of jointing, dyke orientation, and faulting has established that the regional joint pattern was present at an early stage and was added to under favourable circumstances. The Mutton Bay intrusion assumed the regional joint pattern as well as developing new joint orientations of its own. The younger dykes intruded joints that were tensional at the time of intrusion.

11. Three separate periods of mineralization are recognized.

FURTHER WORK

It is hoped that this thesis will form a basis for further detailed investigations along some of the lines followed by the author. The area is ideally suited for certain studies because of its abundant exposure and fair accessibility.

Much valuable work can be done on the gneisses from a detailed structural point of view as many major folds are completely exposed near the coast. The area offers a very complete stratigraphic sequence which should be studied in detail. Near-complete exposure is necessary when means of correlating beds are few.

The geology between Mutton Bay and the Wakeham quartzites is important to the regional study. Also of importance is the relation between the Mutton Bay gneisses and the anorthosite to the northwest.

The Mutton Bay intrusion offers an abundance of well exposed igneous geology. Much is still to be done on the chemistry of the minerals of the plutonic rocks and some chemical work is being done at present by the author on the amphiboles and biotites. The trace element distribution is also expected to make an interesting investigation.

The dyke rocks have hardly been touched by the author and work is at present being done on the dykes by J.Gerencher at Pennsylvania State University, U.S.A.

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APPENDIX I

A recent report by Gerencher and Gold (1967), received too late for consideration in the main body of this thesis, contains important data on the igneous rocks of the Mutton Bay area. The report includes a structural, petrological, geochemical, and palaeomagnetic study of the dyke rocks. The more important observations and conclusions of Gerencher and Gold are listed below.

1. Structural studies and field relations of dykes and fractures indicate that the dykes are preferentially oriented parallel to the coast, but have no definitive relationship to the fractures.
2. Chemical analyses of two samples from the Mutton Bay pluton closely approximate that of the average peralkaline syenite from Nockold's (1954) averages.
3. The petrology and geochemistry of the dykes shows that they can be divided into two groups, aplite and post-aplite dykes.
4. Magnetic studies on 21 samples, including 2 of the Mutton Bay syenite pluton, did not yield a constant palaeomagnetic vector and no palaeomagnetic age date was possible.
5. An altered carbonate-bearing olivine gabbro has a peculiar high potash content.
6. Certain basic dykes were found to contain a little nepheline.

Discussion

The detailed petrological and geochemical study of Gerencher and Gold confirms the subdivision of the dykes in this thesis. The high potash content of the carbonate-bearing olivine gabbro might be explained in the same way as the potash enrichment in trachyte was explained by the author. The structural study agrees with that in this thesis as far as it goes but it is based on considerably less data.

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APPENDIX II

Suite of representative specimens of igneous rocks from the Mutton Bay area deposited in the Petrological Collection, Department of Geological Sciences, McGill University, Montreal

Author's Sample No.	Dept. No.	Description	Location
A-30	P8650	Coarse-grained green pyroxene syenite	$50^{\circ}49'32''$N ; $58^{\circ}57'42''$W - Baie-Rouge
T-16-31	P8651	Coarse-grained foliated pink syenite	$50^{\circ}46'38''$N ; $59^{\circ}00'31''$W - Mutton Bay
T-16-39	P8652	Coarse-grained massive pink syenite (Younger phase at Mutton Bay)	$50^{\circ}46'40''$N ; $59^{\circ}02'25''$W - Baie du Portage
T-21-3	P8653	Medium-grained greenish to pinkish grey syenite	$50^{\circ}54'33''$N ; $58^{\circ}57'34''$W - Lac Salé
T-15-32	P8654	Medium-grained grey syenite porphyry	$50^{\circ}47'58''$N ; $58^{\circ}59'05''$W - Between Pointe Rouge and Île Mécatina
T-15-16	P8655	Medium- to coarse-grained well foliated grey syenite	$50^{\circ}48'33''$N ; $58^{\circ}58'32''$W - Between Pointe Rouge and Île Mécatina
T-14-6	P8656	Coarse-grained dark greenish grey very well foliated syenite	$50^{\circ}50'14''$N ; $58^{\circ}58'36''$W - Tabatière
T-14-1	P8657	Coarse-grained greyish orange pink very well foliated syenite	$50^{\circ}52'31''$N ; $58^{\circ}58'45''$W - Lac Salé
T-13-4	P8658	Coarse-grained dark greenish grey very well foliated syenite - mafic hybrid	$50^{\circ}50'39''$N ; $58^{\circ}58'29''$W - Tabatière
13	P8659	Younger giant gabbro dyke	$51^{\circ}16'24''$N ; $58^{\circ}39'48''$W - St.Augustin river
D-26-3	P8660	Syenite phase of giant gabbro dyke	$51^{\circ}25'47''$N ; $58^{\circ}36'44''$W - St.Augustin river
L-17-12	P8661	Red trachyte dyke	$50^{\circ}43'55''$N ; $59^{\circ}05'16''$W 3 miles southwest of Mutton Bay

Author's Sample No.	Dept. No.	Description	Location
RD-32-16	P8662	Diabase dyke	50°51'35"N ; 59°04'52"W - Lac du Gros Mécatina
RD-53-36	P8663	Pyroxene lamprophyre	50°47'50"N ; 58°59'12"W - Between Point Rouge and Île Mécatina
RD-35-15	P8664	Carbonatite dyke	50°52'20"N ; 59°04'37"W - Lac du Gros Mécatina
R-55-6	P8665	Late metamorphosed gabbro	51°11'42"N ; 58°59'43"W - Lac du Chevreuil
D-1-9	P8666	Intermediate dyke	51°11'42"N ; 58°33'00"W - Grosse Isle
T-10-11	P8667	Porphyritic granite	51°00'00"N ; 58°42'29"W - Îles Fox
R-50-30	P8668	Aplite related to Mutton Bay intrusion	50°56'35"N ; 58°57'34"W - Île Fecteau